APPLICATION OF GROUNDWATER MODELING TECHNOLOGY FOR EVALUATION OF REMEDIAL ACTION ALTERNATIVES WESTERN PROCESSING SITE, KENT, WASHINGTON

by

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SECTION 1

INTRODUCTION

The goal of this project was to evaluate the use of models in predicting contaminant flow from the Western Processing Hazardous Waste Site in Kent, Washington, while providing technical assistance to the U.S. Environmental Protection Agency (EPA) Region X. This included the development of groundwater flow and contaminant transport models of the site to be used for evaluation of proposed remedial action alternatives.

The specific tasks of the modeling portion of the study included:

- a review of available data and identification of deficiencies;
- development of groundwater flow and contaminant transport models of the study area;
- calibration of the flow and transport models with existing data; and
- evaluation of remedial action alternatives for the site with the calibrated models.

A conceptual model of the flow system was developed based on the available hydrogeologic data. This conceptual model formed the framework for developing the flow and transport numerical models.

The Finite Element Three-Dimensional Groundwater (FE3DGW) code, (Gupta et al., 1979) was used to model the groundwater flow within an area around the Western Processing Site. A finite element grid was developed and the necessary data on geologic structure, boundary conditions, hydraulic conductivities, and hydraulic stress were input into the code.

The three-dimensional Coupled Fluid, Energy, and Solute Transport (CFEST) code (Gupta et al., 1982) was used to model the contaminant transport. CFEST is an extension of FE3DGW in that it uses the same hydrologic data structure and finite element grid. In addition, CFEST includes the necessary parameters to couple contaminant transport with groundwater flow.

The models were calibrated to observed 1984 potentiometric and contamination data provided by EPA Region X. Once calibrated, they were used to predict the effectiveness of six proposed remedial action scenarios: 1) no-action, 2) source removal, 3) cap, 4) source removal combined with a cap, 5) upgradient slurry wall combined with a cap, and 6) pump and treat. The flow model was used to predict alterations in the flow field and volume of water removed, while the transport model was used to predict the mass of contaminant removed and average concentrations up to 25 years into the future.

A simplified analytical approach was also used to analyze remedial actions for the site. This action was taken to demonstrate the applicability of an analytical approach versus use of a fully three-dimensional numerical modeling approach.

SECTION 2

CONCLUSIONS

A groundwater flow and contaminant transport model of the Western Processing Site has been developed and calibrated. An acceptable calibration was achieved both in terms of matching model-predicted to observed hydraulic potentials and trichloroethylene (TCE) concentrations, as well as accurately predicting the flow rate of Mill Creek and the concentration of TCE in the creek. The model as it currently exists provides an excellent base on which future calibration and validation can build as more data become available.

The model results show that Mill Creek has been and will continue to be, the primary discharge point for TCE migrating from the Western Processing Site. By 1983, almost half of the TCE that was estimated to have entered the flow system during site operation had exited to Mill Creek. Over the next 25 years (1984 through 2008), the no-action predictions show about 60% of the remaining TCE will discharge to Mill Creek.

Of the total mass originally disposed of at the site, 20% remains in the flow system 25 years after the source removal action was implemented. Similarly, 5% remains after 25 years of the pump and treat remedial action. With both the source removal and pump and treat remedial actions, the mass of TCE discharging to Mill Creek will be reduced by about 50% over the next 25 years (1984 through 2008). None of the actions simulated in the model will prevent TCE from discharging to the creek.

It was found that placing a cap over the site provides very little benefit because the majority of the TCE has already entered, and is being transported by the groundwater system. A slurry wall, as simulated in the model, was shown to be ineffective for altering the groundwater flow patterns and reducing the discharge of TCE to the creek.

Because the creek is a natural discharge point for contamination, a remedial action that should be considered is allowing the creek to act as a natural collection point for treatment. If an initial, short-term solution is desired, the pump and treat and source removal remedial actions will remove the largest amount of contamination in the shortest period of time. These actions also significantly reduce the contaminant load discharging to Mill Creek and could lower contaminant concentrations in the creek to acceptable levels.

The results presented in this report provide a preliminary assessment of remedial actions proposed for the Western Processing Site. Only a single simulation was performed for each action; sensitivity and optimization runs were not performed. While more work can and should be done with the model, this initial effort has provided valuable insight into the relative performance of the remedial actions simulated.

As part of this project, an analytical solution was used in conjunction with the CFEST model to analyze the pump and treat remedial action. The intent was to determine if simple analytical solutions can be of value in analyzing complex data sets. While the analytical solution proved to be of some use in determining a reasonable pumping rate for wells at the Western Processing Site, its overall usefulness was limited. Analytical solutions are suitable for evaluating simple hydrologic systems, but they are of limited value when evaluating complex data sets (i.e., multiple hydrostratigraphic layers; variable hydraulic conductivities, porosities, storage coefficients, recharge, and pumping depths; and stream/aquifer interactions) such as exists at the Western Processing Site.

SECTION 3

DESCRIPTION OF THE STUDY AREA

The Western Processing Site is located within the City of Kent, approximately four miles (6 km) north of the business district (Figure 1). The facility occupies an area of about 13 acres (5 ha), and when in operation consisted of a small laboratory, a solvent recycling plant, a fertilizer plant, bulk storage tanks, drum storage areas, piles of flue dust, construction debris, and large cement-block above-ground storage lagoons for liquid wastes, cooling water, and process water (EPA, 1983). Mill Creek, also known as King County Drainage Ditch No. 1, runs across the northwest corner of the site from south to north. A drainage ditch, bicycle trail, and railroad tracks run along the eastern boundary of the site.

CLIMATE

The annual average rainfall at the Western Processing Site is 39 in. (99 cm). There is a well defined dry season in the summer and a rainy season in the winter. Table 1 shows the monthly average of precipitation, potential evapotranspiration, and actual evapotranspiration. The amount of precipitation that recharges the aquifer was estimated to range from 4 to 12 in./yr (10 to 30 cm/yr). Using a method described by Dunne and Leopold (1978), a recharge of 10 in./yr (25 cm/yr) was obtained. Where water is ponded on the Western Processing Site, it was assumed that very little runoff occurs and 22 in./yr (56 cm/yr) of recharge is possible. A detailed description of recharge calculations is contained in Appendix A.

GEOLOGY

The Western Processing Site lies in the broad flood plain of the Green River. Elevations in this valley average 20 ft (6 m) above mean sea level.

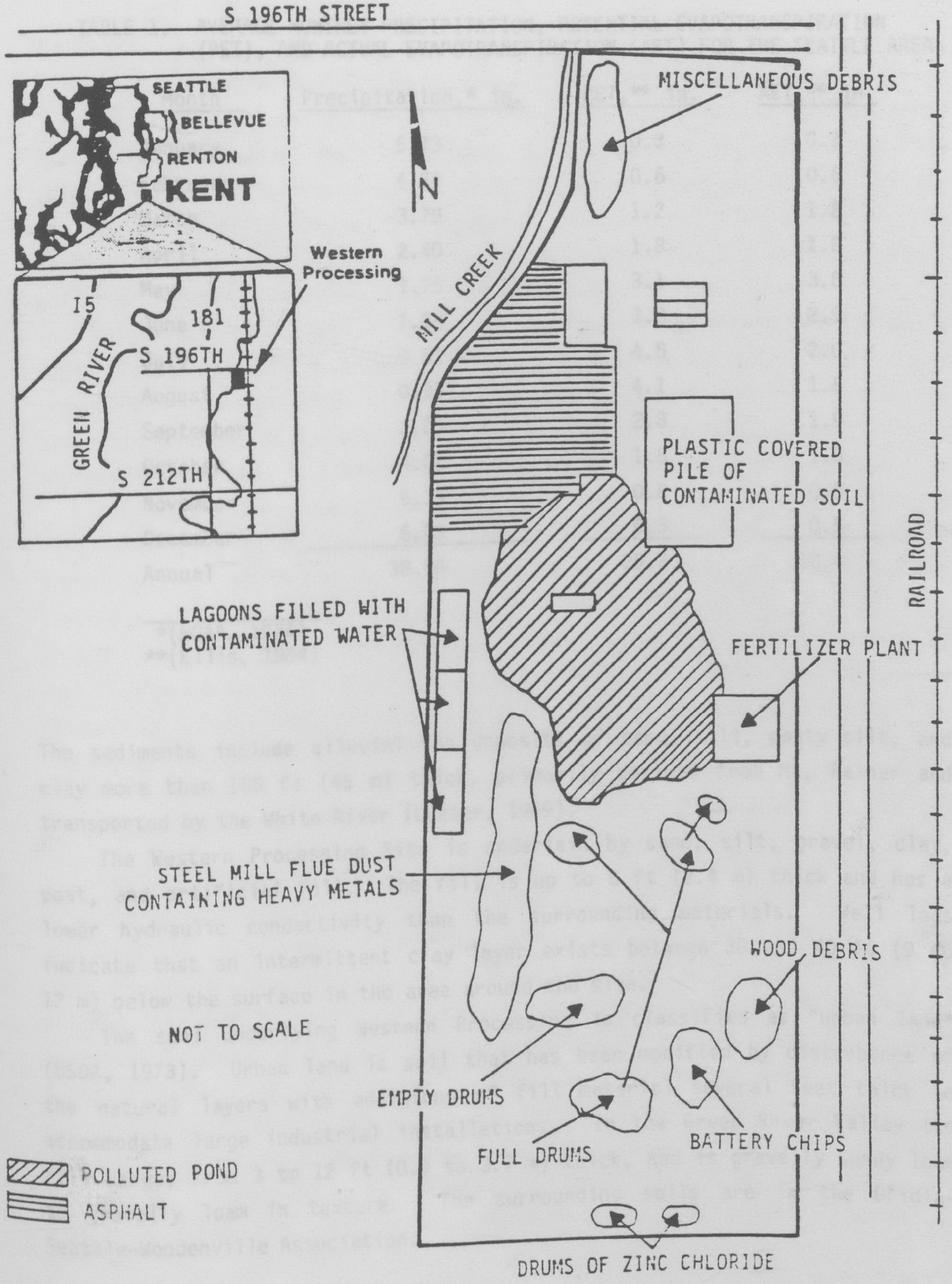

Figure I. Western Processing Location Map.

TABLE 1. AVERAGE MONTHLY PRECIPITATION, POTENTIAL EVAPOTRANSPIRATION (PET), AND ACTUAL EVAPOTRANSPIRATION (AET) FOR THE SEATTLE AREA

Month	Precipitation,* in.	PET,** in.	AET,** in.
January	5.73	0.3	0.3
February	4.24	0.6	0.6
March	3.79	1.2	1.2
April	2.40	1.8	1.8
May	1.73	3.1	3.0
June	1.58	3.8	2.9
July	0.81	4.5	2.0
August	0.95	4.1	1.6
September	2.05	2.8	1.9
October	4.02	1.8	1.8
November	5.35	0.8	0.8
December	6.29	0.5	0.5
Annual	38.94	25.3	18.4

*(NOAA, 1974)
**(Ellis, 1984)

The sediments include alluvial fan deposits of sand, silt, peaty silt, and clay more than 150 ft (45 m) thick, primarily derived from Mt. Rainer and transported by the White River (Luzier, 1969).

The Western Processing Site is underlain by sand, silt, gravel, clay, peat, and artificial fill. The fill is up to 8 ft (2.4 m) thick and has a lower hydraulic conductivity than the surrounding materials. Well logs indicate that an intermittent clay layer exists between 30 and 40 ft (9 to 12 m) below the surface in the area around the site.

The soil underlying Western Processing is classified as "urban land" (USDA, 1973). Urban land is soil that has been modified by disturbance of the natural layers with additions of fill material several feet thick to accommodate large industrial installations. In the Green River Valley the fill ranges from 3 to 12 ft (0.9 to 3.7 m) thick, and is gravelly sandy loam to gravelly loam in texture. The surrounding soils are in the Oridia-Seattle-Woodenville Association.

HYDROLOGY

The water table has been encountered at very shallow depths ranging from 3 to 12 ft (1 to 4 m) and averages 6 ft (2 m) below ground surface (EPA, 1983). A groundwater mound is present in the central portion of the site (Figure 2) due to increased infiltration of ponded water at the surface and the low permeability of the fill material. Groundwater flow directions are shown in Figure 2. Localized flow is to Mill Creek and the drainage ditch, while the regional flow is to the northwest toward the Green River.

Comparison of potential values of well pairs for March through July, 1984 (Table 2) indicates that the Western Processing Site itself is a groundwater recharge area. The groundwater mound has created a downward hydraulic gradient to at least to 30 ft (9 m) below the surface, and the area surrounding the site is a discharge area (upward hydraulic gradient).

Transmissivities calculated by CH2M HILL from pumping and slug tests range from 11.5 to 22,400 gpd/ft (1.4×10^{-1} to 278 m^2/day), and average 3,620 gpd/ft (45 m^2/day). Conductivities (transmissivity divided by thickness of gravel pack) range from 0.8 to 743 gpd/ft^2 (3.3×10^{-2} to 30 m/day) and average 127 gpd/ft^2 (5.2 m/day). Laboratory permeability tests were performed by CH2M HILL on sediment samples from Wells 35 through 44 (Figure 3). These values range from 6.7×10^{-3} to 70 gpd/ft^2 (3×10^{-4} to 2.9 m/day) and average 8.5 gpd/ft^2 (0.35 m/day).

WASTE DISPOSAL HISTORY

Western Processing began operation in 1957 as an animal by-products and brewer's yeast processor. Since that time the operation expanded to include the handling of solvents, flue dust, battery chips, acids, cyanides, and a wide variety of industrial wastes (EPA, 1983). In 1982, the EPA found 26 priority pollutants in the surface waters around the site, all of which were subsequently found in on-site soil and groundwater samples. As a result of these findings, the EPA issued an order to require the owner to conduct monitoring to ascertain the nature and extent of the hazard that exists at the site. After the owner declared himself unable to carry out the necessary monitoring, a court order was obtained to allow the EPA to investigate the site. As a result of this action, disposal at the site ceased in 1982. In

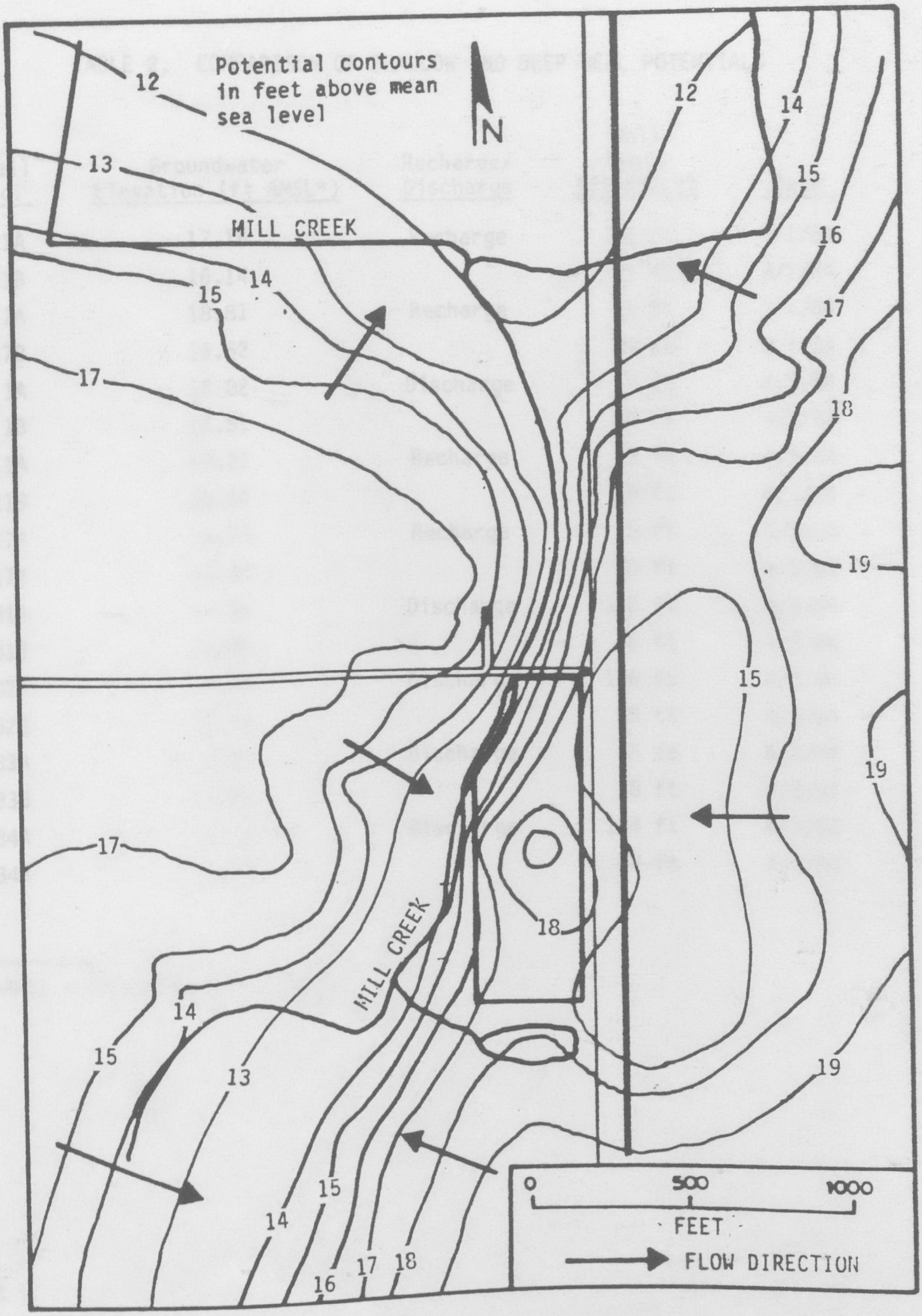

Figure 2. Smoothed Kriged Potential Surface for April, 1984.

TABLE 2. COMPARISON OF SHALLOW AND DEEP WELL POTENTIALS

Well No.	Groundwater Elevation (ft AMSL*)	Recharge/ Discharge	Well Depth (ft AMSL*)	Date
11A	17.16	Recharge	12 ft	3/1/84
11B	16.14		29 ft	3/1/84
17A	18.81	Recharge	15 ft	3/1/84
17B	15.62		30 ft	3/1/84
1A	15.02	Discharge	12 ft	4/3/84
1B	15.51		30 ft	4/3/84
11A	17.25	Recharge	12 ft	4/3/84
11B	16.14		29 ft	4/3/84
17A	19.73	Recharge	15 ft	4/3/84
17B	15.45		30 ft	4/3/84
31A	17.24	Discharge	150 ft	4/3/84
31B	16.07		55 ft	4/3/84
32A	17.49	Discharge	106 ft	4/3/84
32B	15.49		28 ft	4/3/84
33A	18.67	Discharge	65 ft	4/3/84
33B	15.99		38 ft	4/3/84
34A	18.07	Discharge	134 ft	4/3/84
34B	16.13		62 ft	4/3/84

*AMSL = Above Mean Sea Level

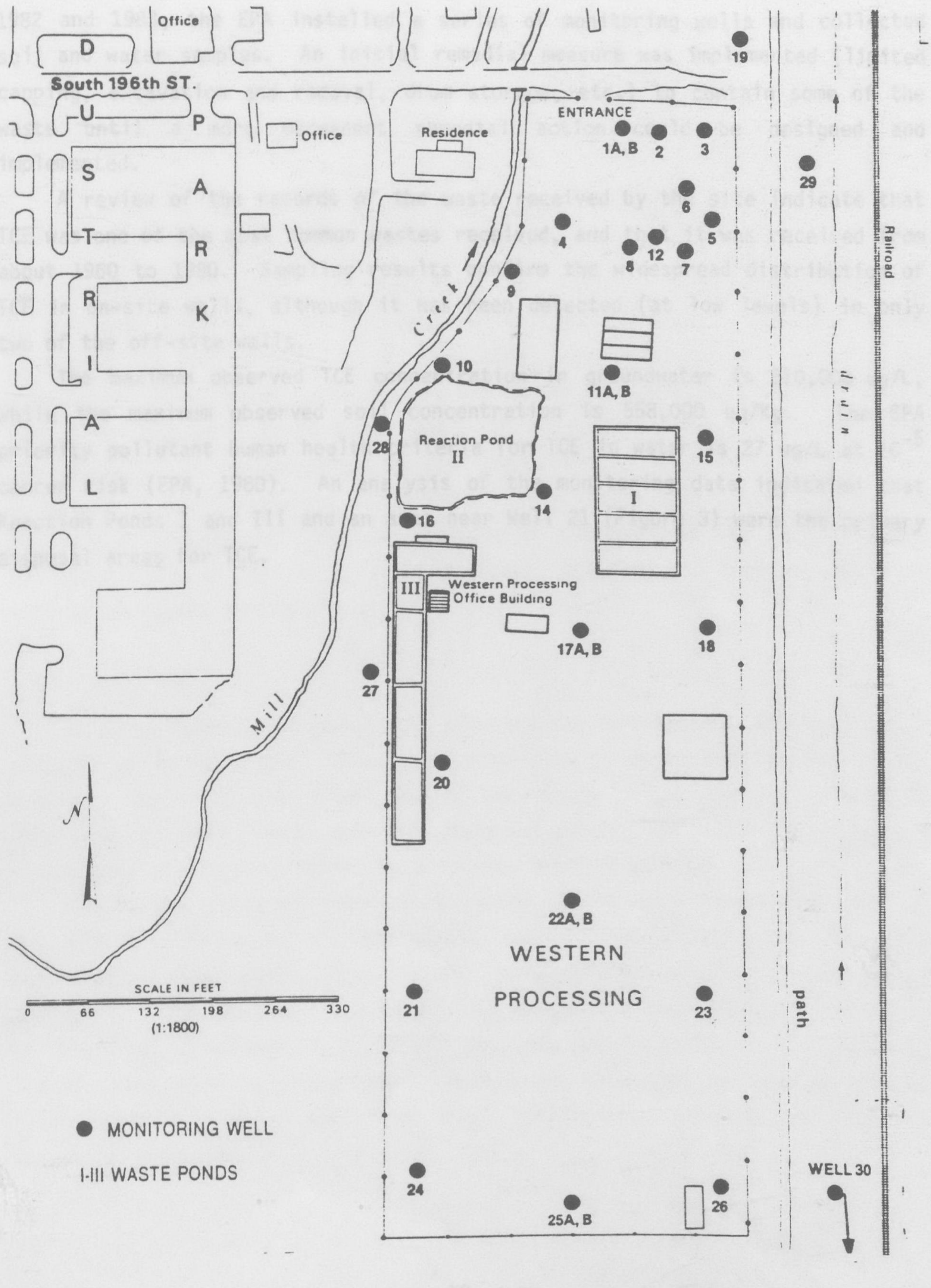

Figure 3. Western Processing Well and Waste Pond Locations.

1982 and 1983, the EPA installed a series of monitoring wells and collected soil and water samples. An initial remedial measure was implemented (limited capping, excavation and removal, drum storage, etc.) to contain some of the waste until a more permanent remedial action could be designed and implemented.

A review of the records of the waste received by the site indicate that TCE was one of the most common wastes received, and that it was received from about 1960 to 1980. Sampling results confirm the widespread distribution of TCE in on-site wells, although it has been detected (at low levels) in only two of the off-site wells.

The maximum observed TCE concentration in groundwater is 210,000 ug/L, while the maximum observed soil concentration is 558,000 ug/Kg. The EPA priority pollutant human health criteria for TCE in water is 27 ug/L at 10^{-5} cancer risk (EPA, 1980). An analysis of the monitoring data indicated that Reaction Ponds I and III and an area near Well 21 (Figure 3) were the primary disposal areas for TCE.

SECTION 4

MODEL DEVELOPMENT

A numerical model was developed to simulate groundwater flow and contaminant transport at the Western Processing Site. The model was developed in two steps: 1) a flow model was developed to describe the groundwater flow in the area around the Western Processing Site; and 2) the flow model was used to form the basis of a transport model which simulated the movement of contaminants in the groundwater. Although the model was developed in two stages, the final result is a single model which can be used to simulate groundwater flow and contaminant transport at the site. Because the model was developed in a staged approach, the flow and transport portions will be discussed separately.

MODEL SELECTION

A three-dimensional model was selected for the Western Processing Site because it is able to: simulate variations in permeability with depth; simulate the vertical flow within the study area; simulate localized discharge to Mill Creek and the drainage ditch; and accurately simulate slurry wall and pumping depths in proposed remedial actions.

The numerical codes selected to model the Western Processing Site are the FE3DGW flow code and the CFEST code. The FE3DGW code simulates groundwater flow while its sister code, CFEST, simulates contaminant transport. The two codes are completely compatible such that the simulation of transport phenomena using CFEST proceeds directly from calibration of FE3DGW based on flow properties. Both codes have been benchmarked against other numerical codes and have been verified by solution of standard analytical problems.

REGIONAL MODEL

The original approach to modeling the Western Processing Site included the development of a regional model to describe flow within the valley surrounding Western Processing. This regional model, to include the area within a 1.5 mile (2.4 km) radius of the site, would have established boundary conditions for the local model. The regional model was also intended to establish reasonable transmissivities for the study area since the reported values ranged over three orders of magnitude.

In reviewing the data for the regional system, it was determined that sufficient data to calibrate this model were not available and could not be obtained within the time frame of this study; therefore, only a local model was developed. Transmissivities and boundary conditions for the local model were estimated from the available data and adjusted in the model calibration process. Additional data collection efforts by EPA Region X aided in verifying some of the estimated parameters.

GROUNDWATER FLOW MODEL DEVELOPMENT

The flow model of the local area around the Western Processing Site was developed based on the available hydrogeologic data. The model area is 2,790 ft (850 m) wide and 4,020 ft (1,225 m) long. The Western Processing Site is located near the center of the model region (Figure 4).

A finite element grid was developed for the local model region to properly represent the areal extent, boundary conditions, and primary features of the hydrologic system. The grid consists of 311 nodes and 283 elements. The two-dimensional surface representation of the grid is shown in Figure 5.

Data files were developed for the aquifer thickness and extent, vertical and horizontal hydraulic conductivity, and hydraulic stress (recharge and discharge) using data received from EPA Region X. The data used in the final calibrated flow model are discussed below.

Structure

The top 100 ft (30 m) below the water table was simulated in the model. The top 30 ft (9 m) was simulated as a silt and fine sand material, except

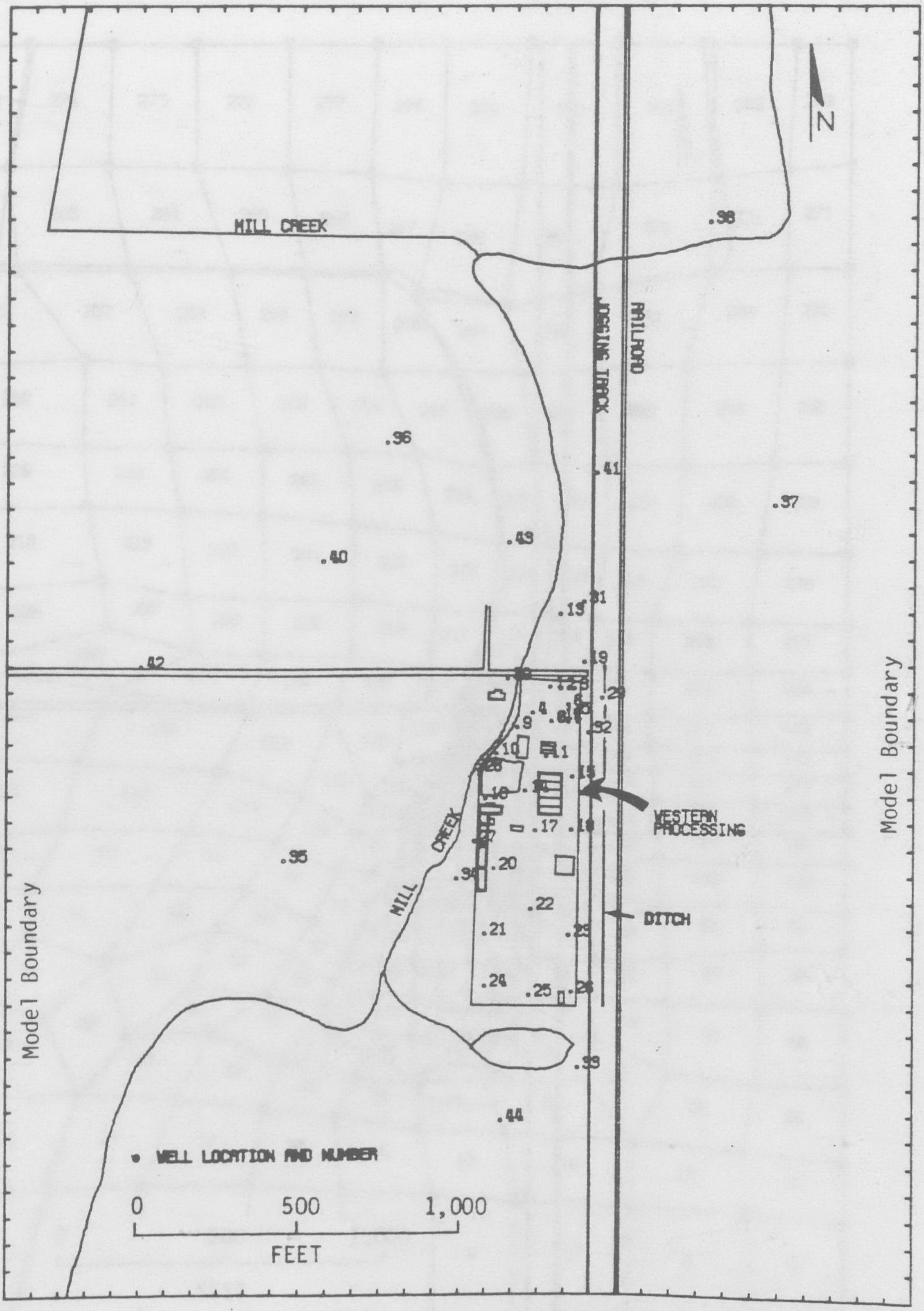

Figure 4. Western Processing Model Area.

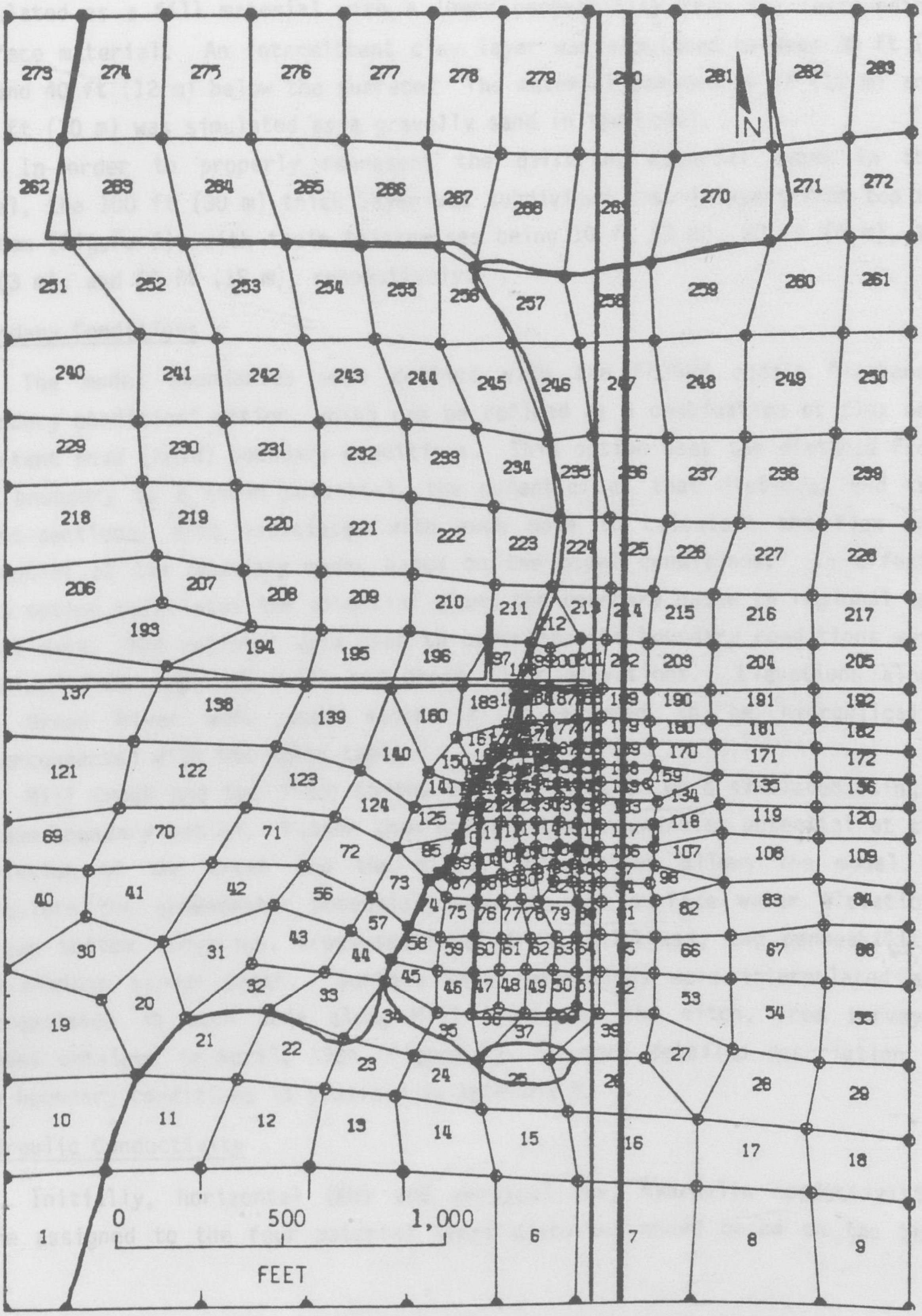

Figure 5. Finite Element Grid of the Western Processing Site.

that directly below the Western Processing Site where the top 10 ft (3 m) was simulated as a fill material with a lower permeability than the surrounding surface material. An intermittent clay layer was simulated between 30 ft (9 m) and 40 ft (12 m) below the surface. The material between 40 ft (12 m) and 100 ft (30 m) was simulated as a gravelly sand in the model.

In order to properly represent the different material types in the model, the 100 ft (30 m) thick layer was subdivided into 4 layers from top to bottom (Figure 6), with their thicknesses being 10 ft (3 m), 20 ft (6 m), 10 ft (3 m), and 60 ft (18 m), respectively.

Boundary Conditions

The model boundaries were defined with the FE3DGW code's "leakance boundary condition" option, which can be defined as a combination of flux and constant head (held) boundary conditions. This option uses the distance from the boundary to a known potential, the potential at that distance, and the cross-sectional area associated with each node to calculate the flux and potential at the boundary nodes based on the model conditions. In effect, this option calculates the potential along the boundary based on regional and local data. The regional data used to calculate the boundary conditions were obtained from regional wells and Green River elevations. Elevations along the Green River were used since it is assumed to be hydraulically interconnected with the water table.

Mill Creek and the ditch to the east of the site were simulated using a stream boundary option. Rather than holding the groundwater potential at the elevation of the creek and the ditch, this option allows the model to calculate the groundwater potential based on the surface water elevation; stream bottom elevation, cross-sectional area, thickness, and permeability; and minimum stream depth. Surface water elevations were interpolated and extrapolated at each node along Mill Creek and the ditch, from surveyed values obtained in April, 1984 (Figure 7). A more detailed description of the boundary conditions is provided in Appendix B.

Hydraulic Conductivity

Initially, horizontal (Kh) and vertical (Kv) hydraulic conductivities were assigned to the four material types discussed above based on the best

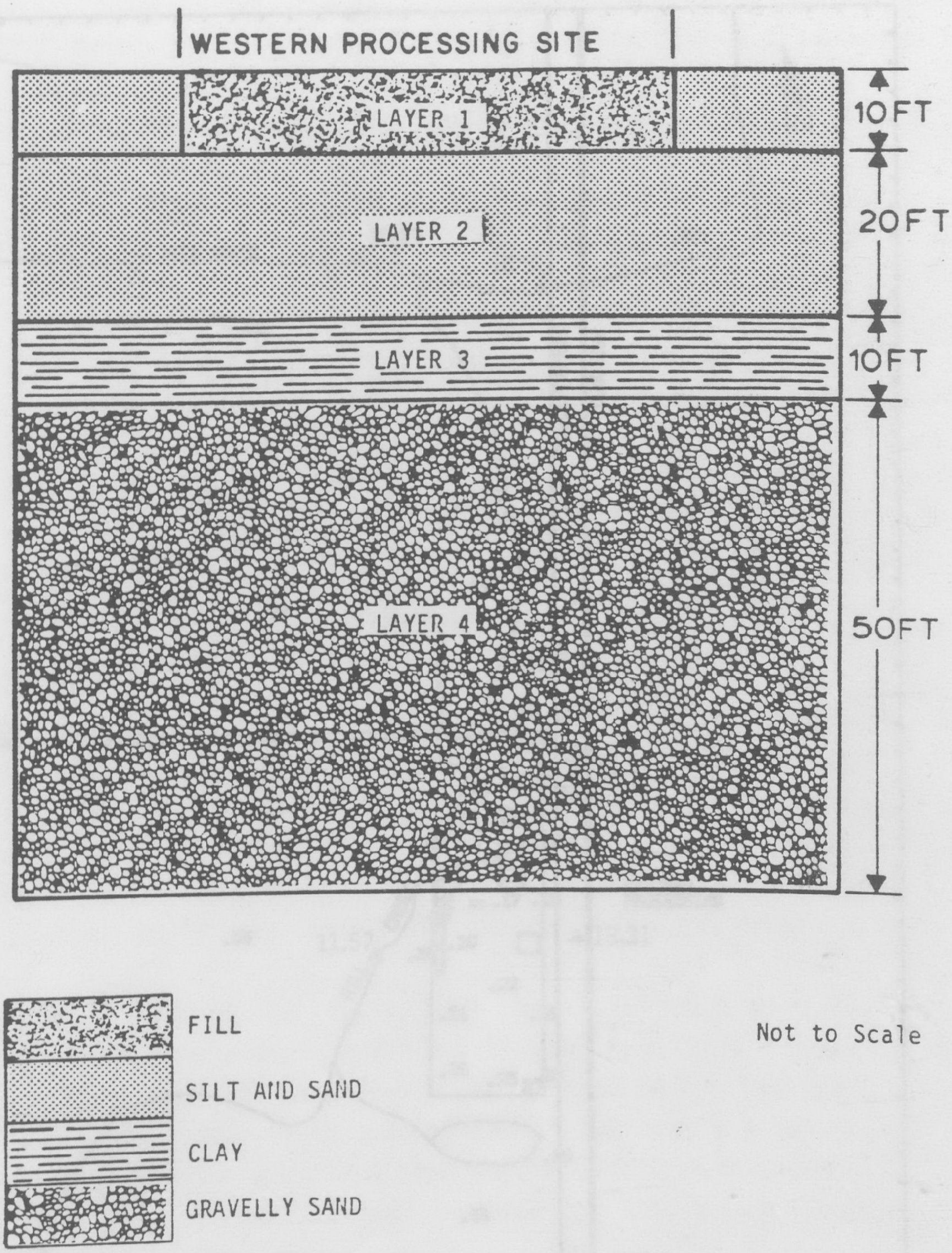

Figure 6. Cross Section Depicting the Structural Layers of the Study Area.

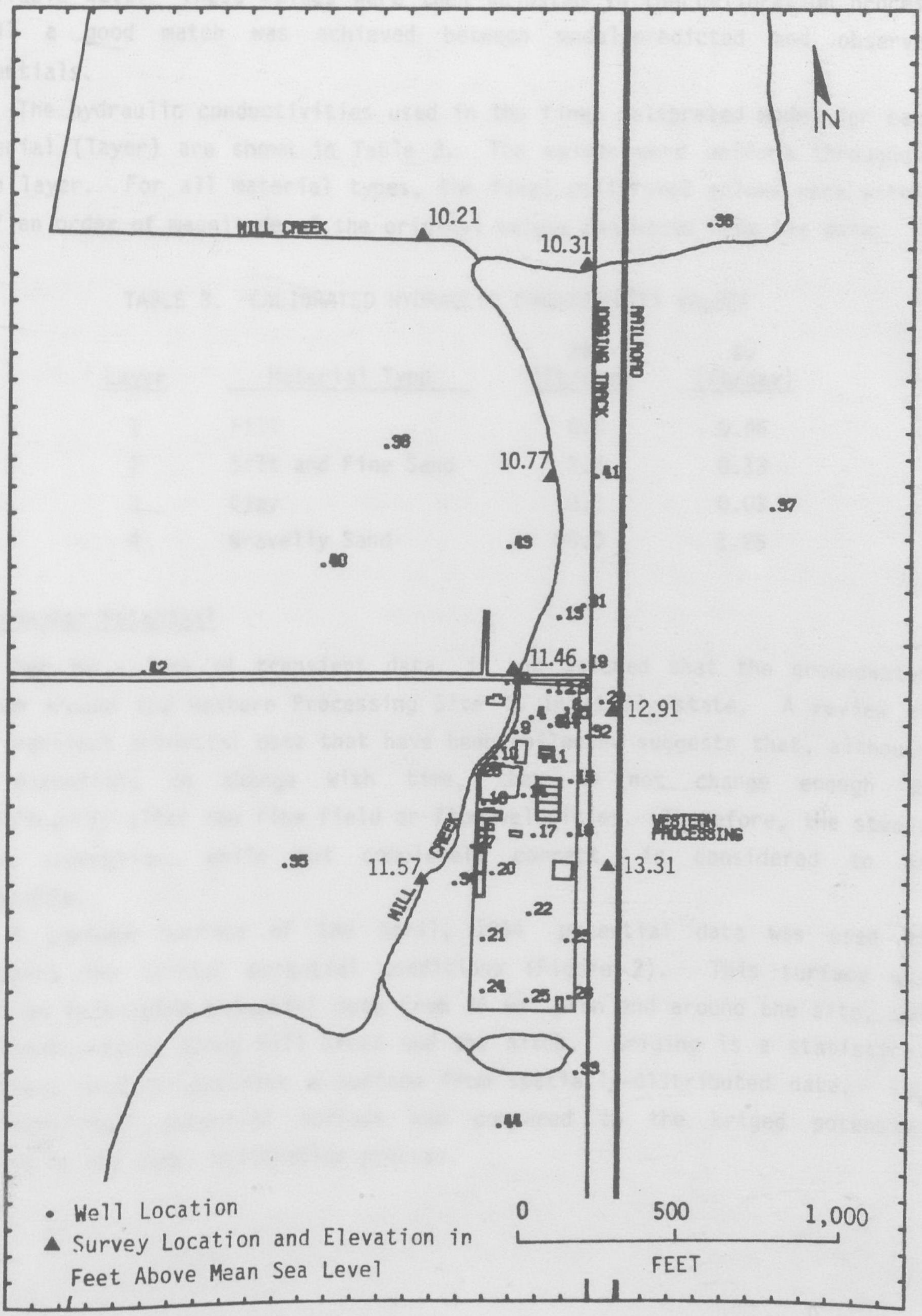

Figure 7. Location of Surveyed Values for Mill Creek and Drainage Ditch.

available data. These values were then adjusted in the calibration process until a good match was achieved between model-predicted and observed potentials.

The hydraulic conductivities used in the final calibrated model for each material (layer) are shown in Table 3. The values were uniform throughout each layer. For all material types, the final calibrated values were within half an order of magnitude of the original values estimated from the data.

TABLE 3. CALIBRATED HYDRAULIC CONDUCTIVITY VALUES

Layer	Material Type	Kh (ft/day)	Kv (ft/day)
1	Fill	0.6	0.06
2	Silt and Fine Sand	2.5	0.13
3	Clay	0.3	0.03
4	Gravelly Sand	25.0	1.25

Groundwater Potential

Due to a lack of transient data, it was assumed that the groundwater system around the Western Processing Site is in steady state. A review of the transient potential data that have been collected suggests that, although the potentials do change with time, they do not change enough to significantly alter the flow field or flow velocities. Therefore, the steady state assumption, while not completely correct, is considered to be acceptable.

A contour surface of the April, 1984 potential data was used to represent the initial potential conditions (Figure 2). This surface was prepared by kriging potential data from 36 wells on and around the site, and from measurements along Mill Creek and the ditch. Kriging is a statistical technique used to estimate a surface from spatially-distributed data. The model-predicted potential surface was compared to the kriged potential surface in the model calibration process.

Hydraulic Stress

The only hydraulic stress considered within the model region was recharge from precipitation. Recharge was assumed constant over the area at 10 in./yr (25 cm/yr). The only exceptions were in the asphalted (capped) area and the area of ponded water on the site (Figure 1) where recharge was set at 0 in./yr and 22 in./yr (56 cm/yr), respectively. A detailed description of the recharge calculations is contained in Appendix A.

Porosity

A porosity of 15% was used in all layers of the model except the clay layer where the porosity was assumed to be 20%.

CONTAMINANT TRANSPORT MODEL DEVELOPMENT

The contaminant transport model was developed using the calibrated flow model, observed or estimated migration parameters, and estimates of source loading on the groundwater system as a function of time. Data input files were developed to define source concentrations, leaching rates, retardation factors, and dispersivity. In most cases, these data were not specifically known for the Western Processing Site. As a reasonable estimate, initial values were selected from the literature and final values were derived in the model calibration process. The data used in the final calibrated transport model are discussed below.

Contaminant Selection

A review of the list of wastes received at the Western Processing Site shows that TCE was accepted for disposal throughout the operating life of the site. Also, high concentrations of TCE have been measured in many of the wells on site and it is one of the ubiquitous contaminants. Therefore, TCE was selected for use in calibrating the transport model, and for comparison of the various remedial action alternatives simulated.

Source Location

A review of the sampling results for TCE in the on-site wells (EPA, 1983) reveals three probable source locations: 1) Reaction Pond I,

2) Reaction Pond III, and 3) near Well 21 (Figure 3). The areas of these three sources were established as 5,700 ft^2 (530 m^2), 4,170 ft^2 (388 m^2), and 2,190 ft^2 (204 m^2), respectively, in the model.

Source Area Concentrations

The model simulated leaching of TCE into the groundwater rather than direct infiltration; therefore, the initial TCE concentration at all three source areas was set at the solubility limit of TCE in water, 1.1 x 10^6 ug/L (Verschueren, 1977). The loading rate at each site can be calculated as the infiltration rate, times the surface area of the source, times the initial TCE concentration at the source. The infiltration rates used in the calibrated model were 6 in./yr (15 cm/yr) at Reaction Pond I, and 10 in./yr (25 cm/yr) at Reaction Pond III and around Well 21. Using the areas and the initial concentration discussed above, the loading rates were estimated at 75 lb/yr (34 Kg/yr), 230 lb/yr (104 Kg/yr), and 300 lb/yr (136 Kg/yr) at Reaction Pond I, Reaction Pond III, and Well 21, respectively.

Source Duration/Leach Rate

The sources were assumed to be actively leaching TCE into the groundwater for 20 years, from 1958 through 1978. After 1978, TCE was no longer considered to be leaching into the groundwater flow system, however, the TCE already introduced was considered to be available for transport.

Sorption/Retardation

During transport through soils, TCE undergoes retardation caused by adsorption. Based on available data, an adsorption coefficient (Kd) of between 0.1 and 1.0 (Richter, 1981) appears reasonable for the site. A Kd of 0.2 was used in the final calibrated model, which corresponds to a retardation factor of 4, for the Western Processing Site. Calculation of the retardation factor is described in more detail in Appendix C.

SECTION 5

MODEL CALIBRATION

The flow and transport models were calibrated by adjusting certain model input parameters until a good match was achieved between model-predicted and observed data. A brief description of the calibration process for both the flow and transport models is provided below.

FLOW MODEL CALIBRATION

Once the data were input into the FE3DGW code, the model was run in the steady-state mode to predict groundwater potentials. The model was calibrated by comparing the model-predicted flow-field to measured potential data.

The difference between model-predicted and measured hydraulic potentials was minimized by adjusting the following flow model parameters: the vertical and horizontal hydraulic conductivity, the parameters controlling the flow to Mill Creek and the drainage ditch (stream bottom permeability and thickness), and the boundary conditions.

The final model-predicted potential surface for the water table (top of Layer 1) (Figure 8) compares well with the kriged potential data (Figure 2) and the conceptual model of the flow regime within the study area (localized flow to Mill Creek and the ditch, and regional flow to the northwest). Potential surfaces for the top of Layers 2, 3, 4, and for the bottom of Layer 4 are shown in Figure 9, 10, 11, and 12, respectively. The model-predicted groundwater flux to Mill Creek along the reach within the study area is 0.3 cfs (734 m^3/day). This value compares well with a gain of 0.5 cfs (1,223 m^3/day) along Mill Creek within the study area as measured in May, 1982, by EPA Region X.

A more thorough description of the changes made in the calibration process and their impact on model results is provided in Appendix D.

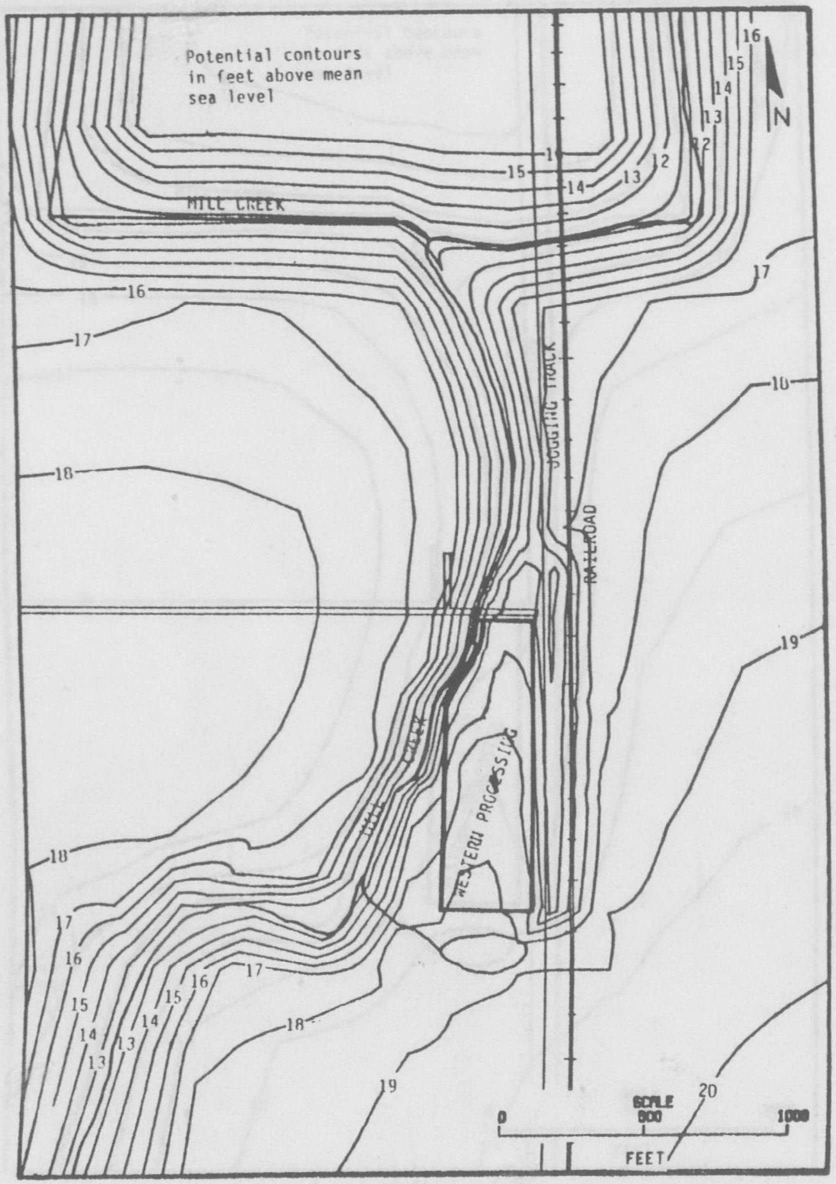

Figure 8. Model-Predicted 1983 Top of Layer 1 Potential Surface for the Base Case Simulation.

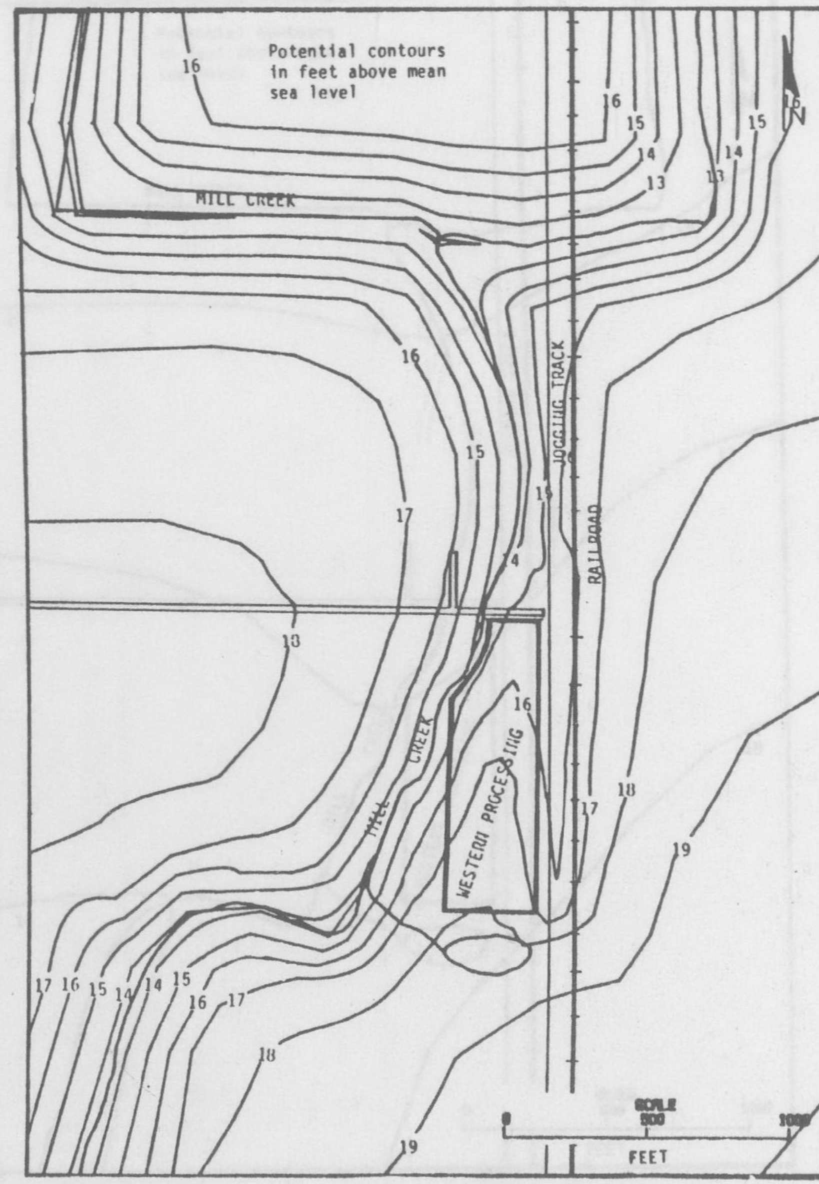

Figure 9. Model-Predicted 1983 Top of Layer 2 Potential Surface for the Base Case Simulation.

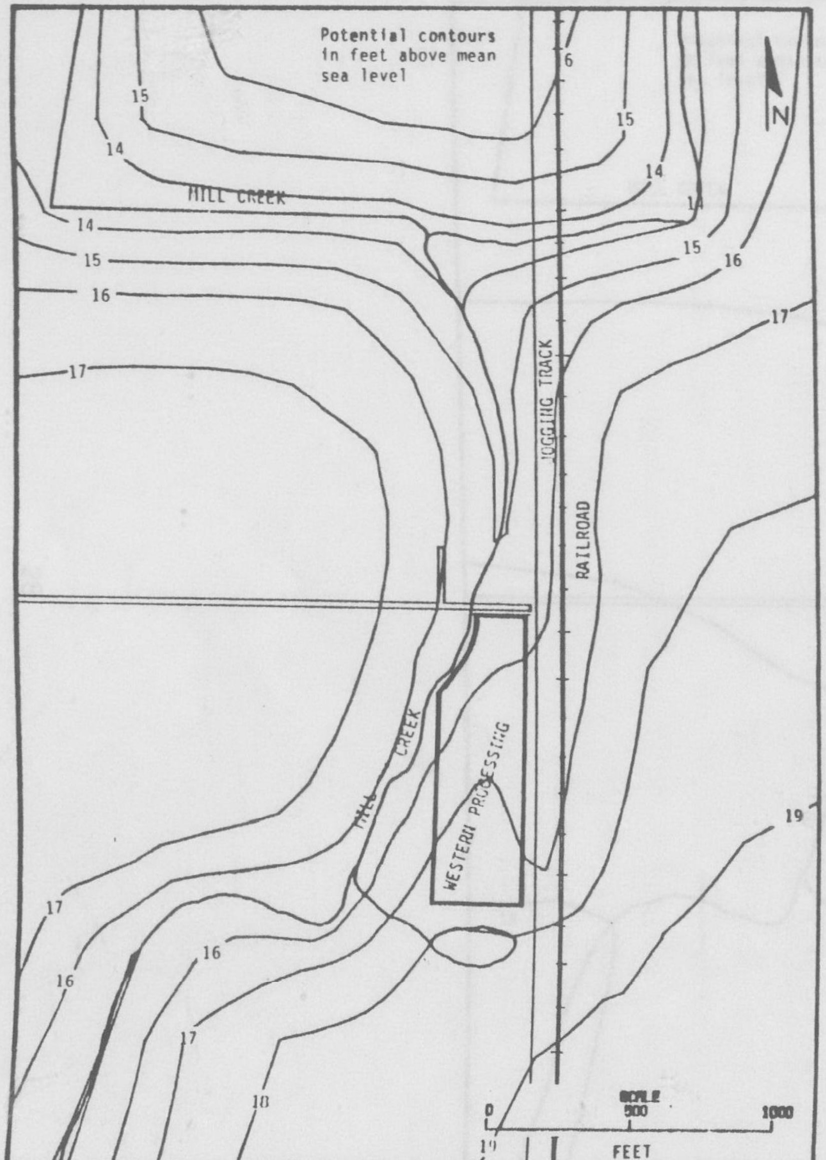

Figure 10. Model-Predicted 1983 Top of Layer 3 Potential Surface for the Base Case Simulation.

Figure 11. Model-Predicted 1983 Top of Layer 4 Potential Surface for the Base Case Simulation.

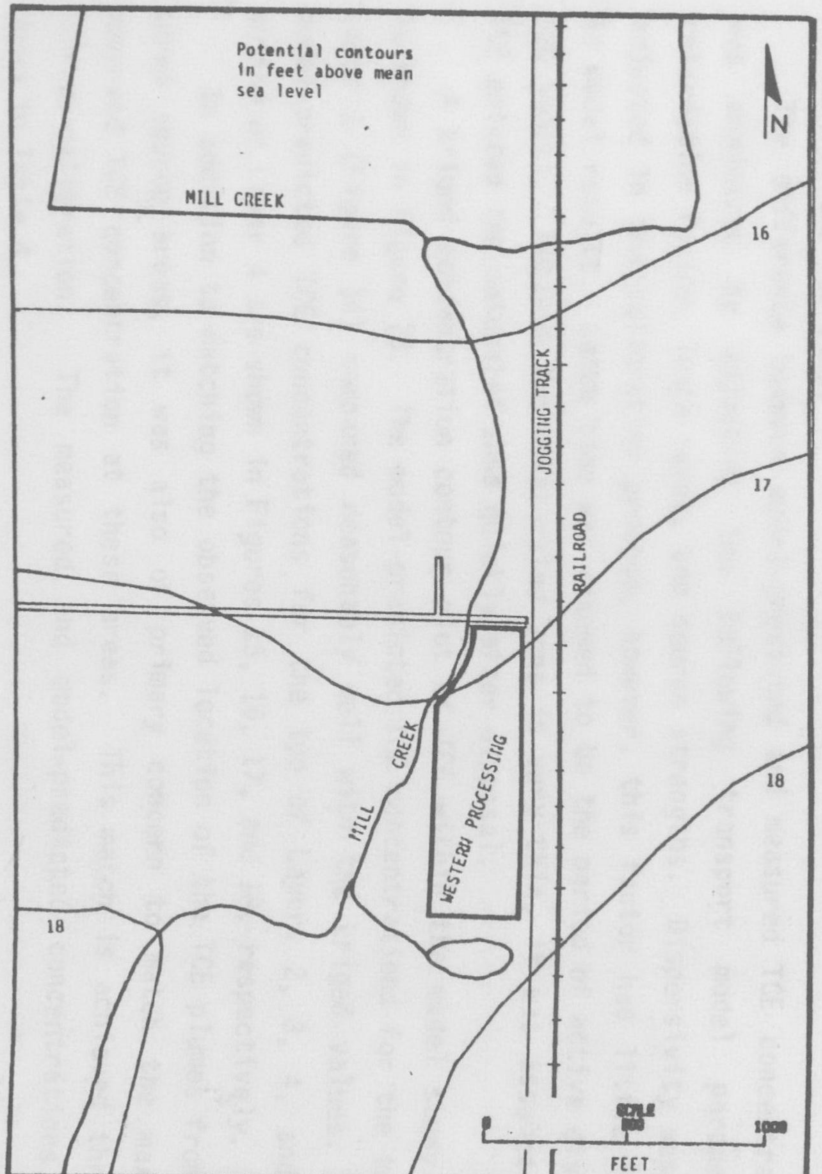

Figure 12. Model-Predicted 1983 Bottom of Layer 4 Potential Surface for the Base Case Simulation.

Regional groundwater flow as predicted by the model is to the northwest, while localized flow is to Mill Creek. Discharge to Mill Creek dominates the flow patterns to a depth of about 30 ft (9 m) and its influence can be seen at 100 ft (30 m). Below 30 ft (9 m) the flow is primarily controlled by the regional gradient.

TRANSPORT MODEL CALIBRATION

Once the data were input into the CFEST code, the model was run in the transient mode with five-year time steps from 1958 to 1983. The model was calibrated by comparing model-predicted TCE concentrations to measured TCE concentrations for 1983.

The difference between model-predicted and measured TCE concentrations was minimized by adjusting the following transport model parameters: retardation factor, leach rates, and source strengths. Dispersivity was also adjusted in the calibration process, however, this factor had little impact on model results. Leach time was assumed to be the period of active disposal (20 years). Because the unsaturated zone is very thin, it was assumed that TCE entered the saturated zone quickly after disposal.

A kriged concentration contour plot of TCE within the model study area is shown in Figure 13. The model-predicted TCE concentrations for the top of Layer 1 (Figure 14) compared reasonably well with the kriged values. The model-predicted TCE concentrations for the top of Layers 2, 3, 4, and the bottom of Layer 4 are shown in Figures 15, 16, 17, and 18, respectively.

In addition to matching the observed location of the TCE plumes from the three source areas, it was also of primary concern to match the maximum observed TCE concentration at these areas. This match is achieved through source calibration. The measured and model-predicted concentrations are shown in Table 4.

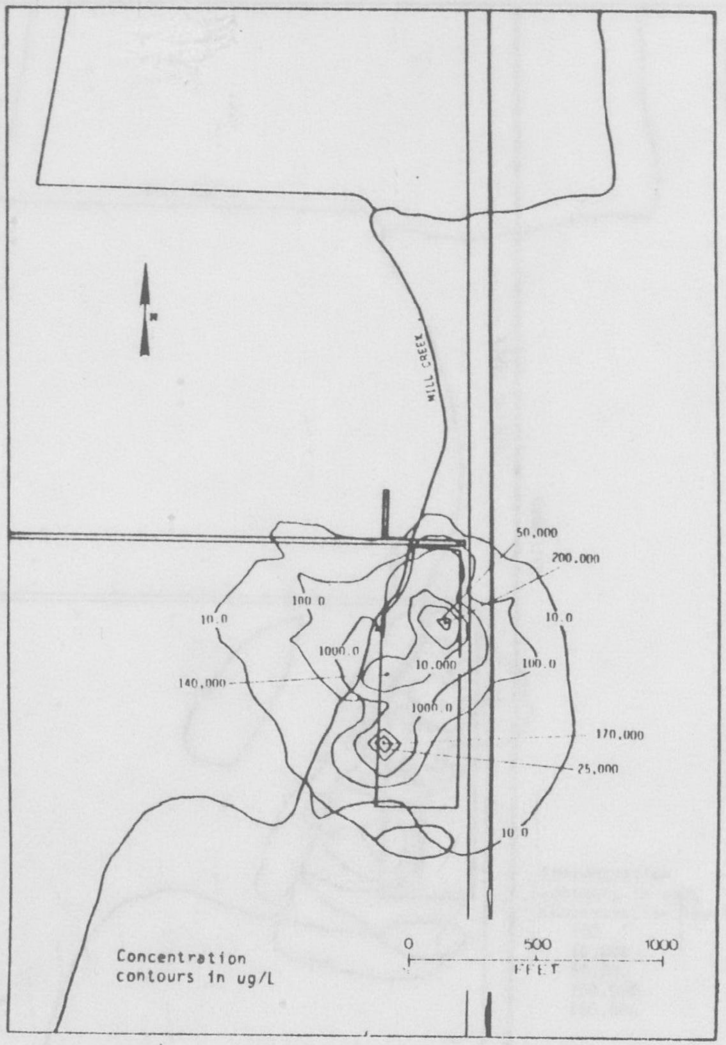

Figure 13. Kriged TCE Concentration Contours.

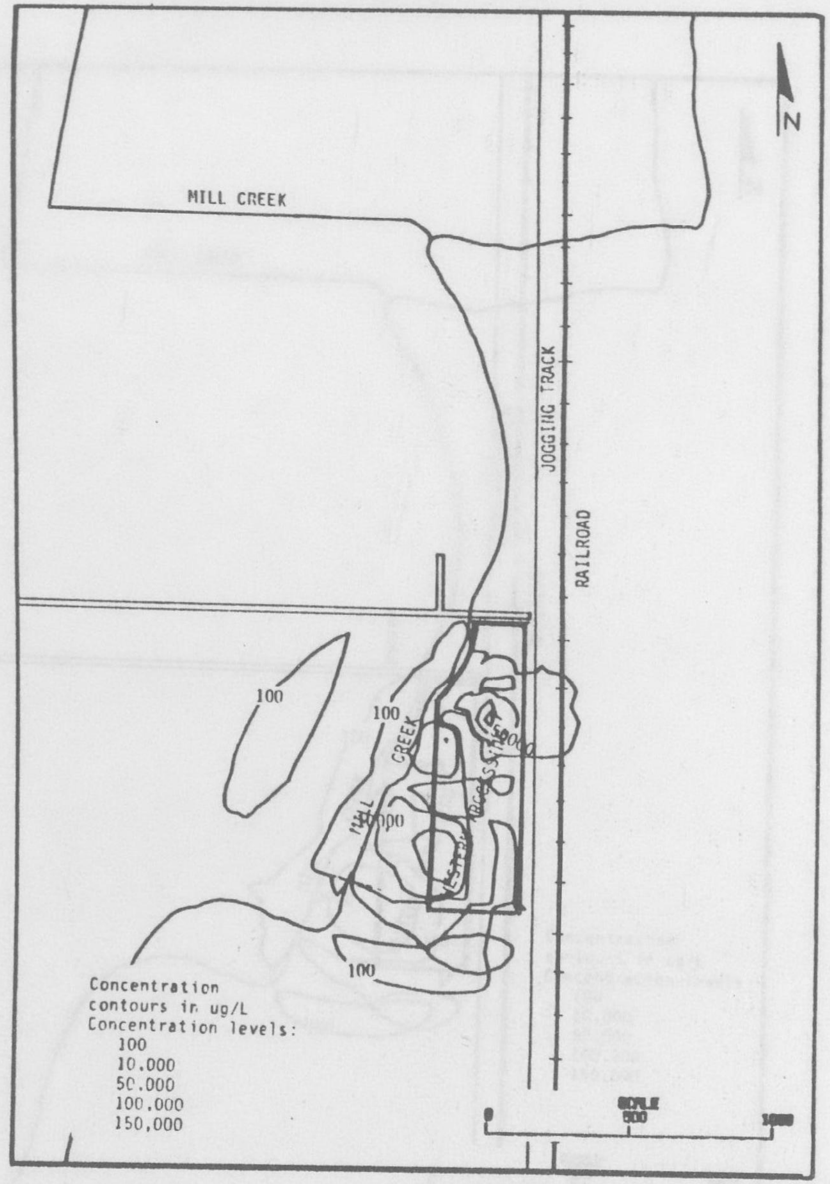

Figure 14. Model-Predicted 1983 Top of Layer 1 TCE Concentration Contours for the Base Case Simulation.

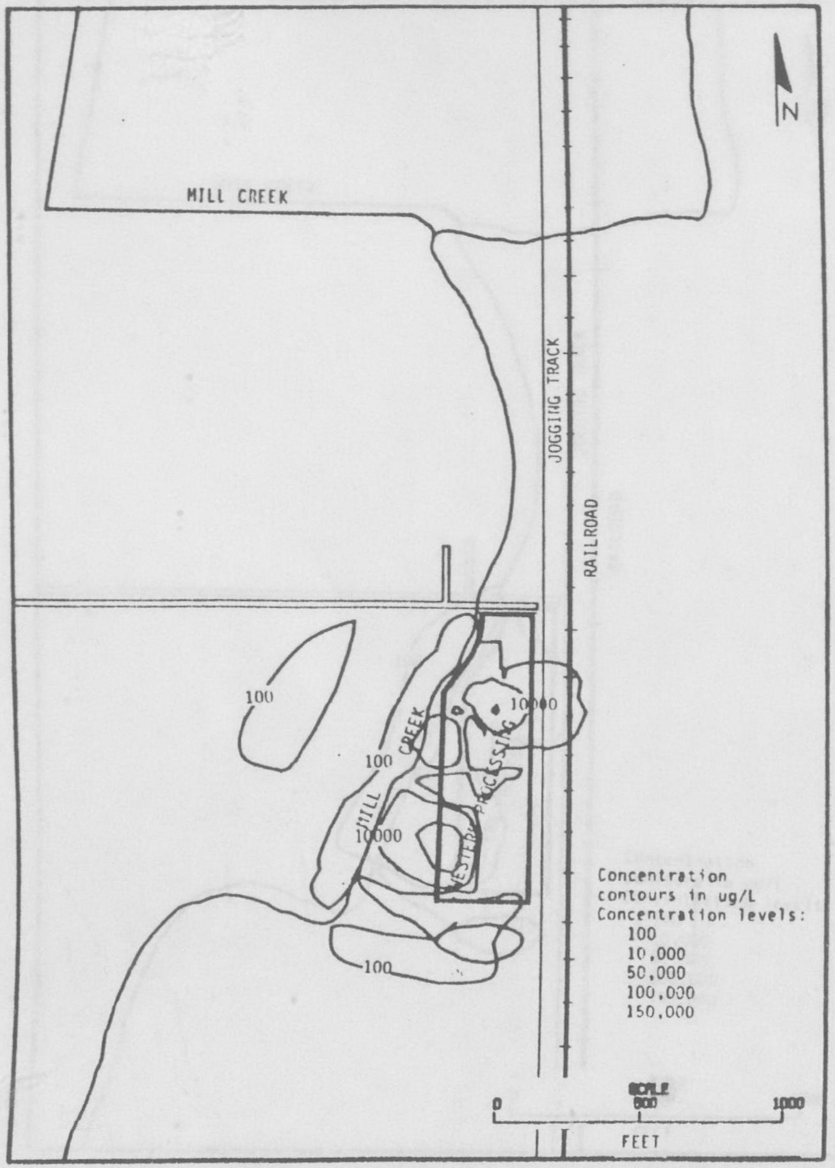

Figure 15. Model-Predicted 1983 Top of Layer 2 TCE Concentration Contours for the Base Case Simulation.

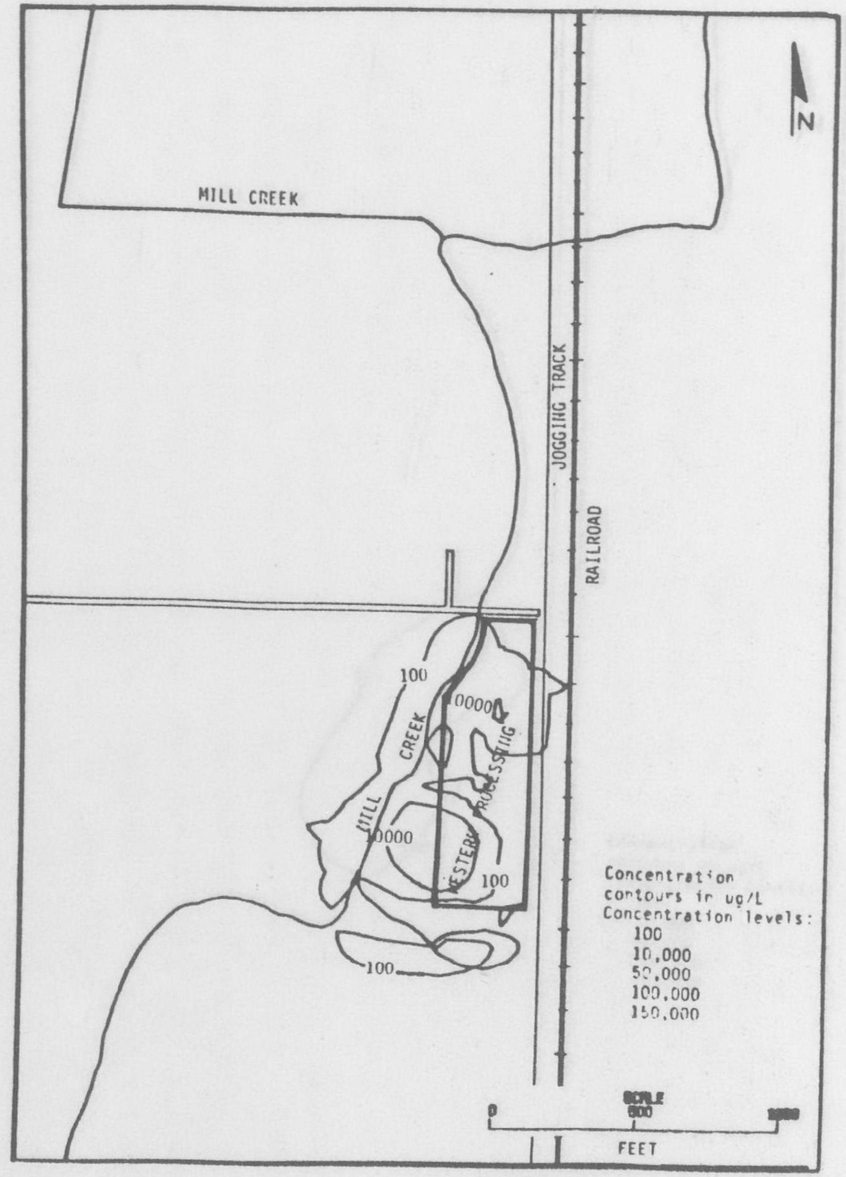

Figure 16. Model-Predicted 1983 Top of Layer 3 TCE Concentration Contours for the Base Case Simulation.

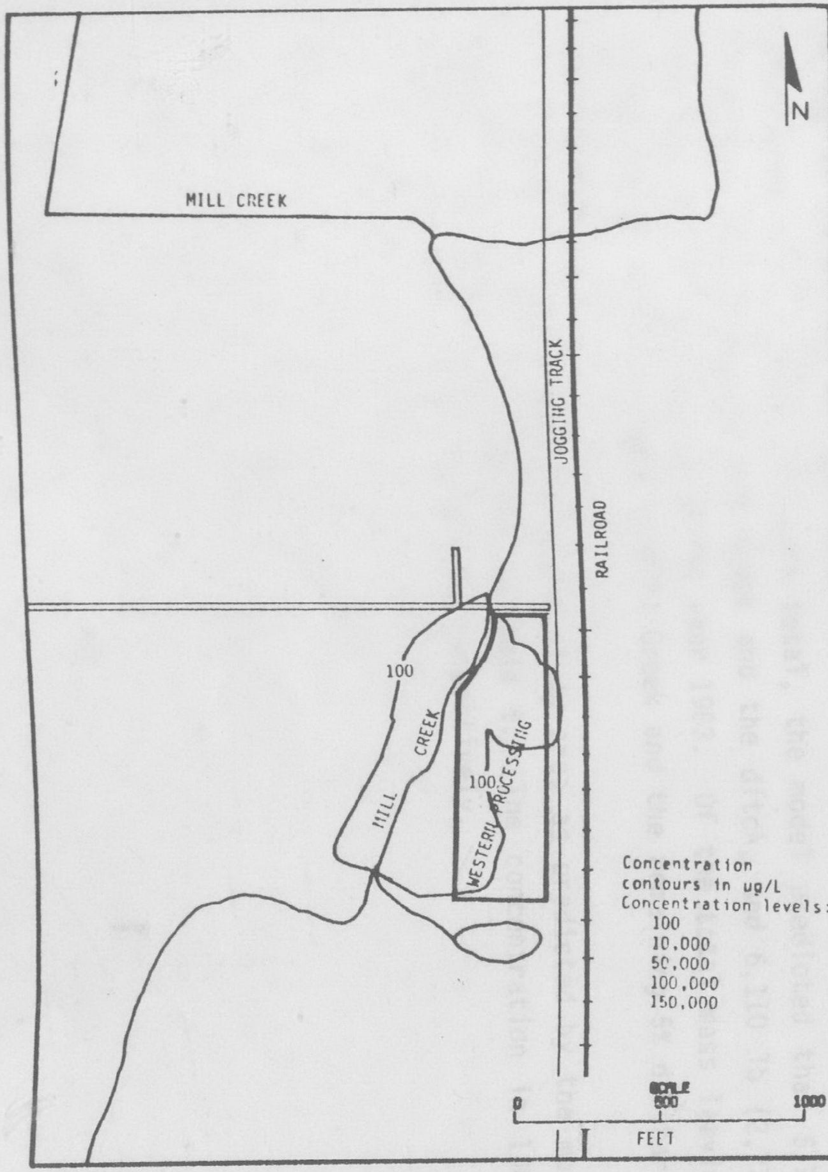

Figure 17. Model-Predicted 1983 Top of Layer 4 TCE Concentration Contours for the Base Case Simulation.

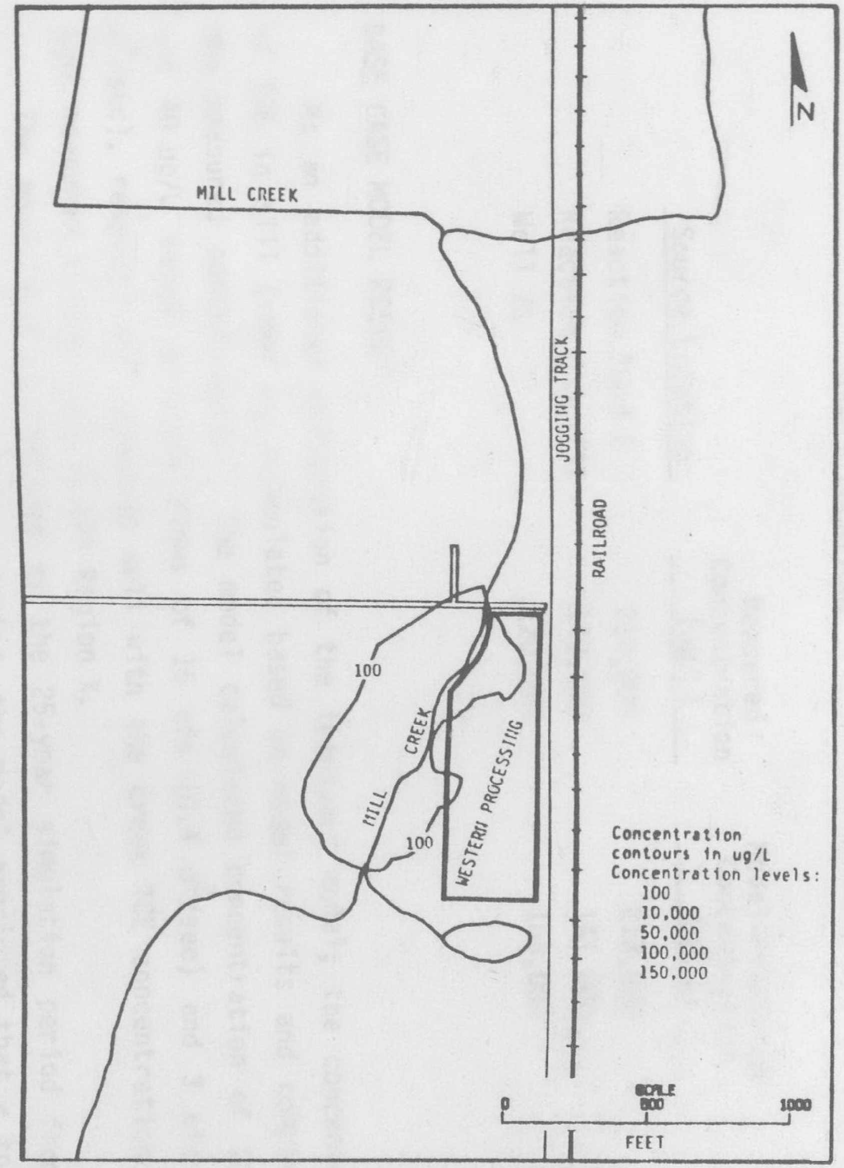

Figure 18. Model-Predicted 1983 Bottom of Layer 4 TCE Concentration Contours for the Base Case Simulation.

TABLE 4. COMPARISON OF OBSERVED TO MODEL-PREDICTED MAXIMUM TCE CONCENTRATIONS IN THE GROUNDWATER AT THE THREE SOURCE LOCATIONS

Source Location	Measured Concentration (ug/L)	Model-Predicted Concentration (ug/L)
Reaction Pond I	210,000	213,000
Reaction Pond III	140,000	141,000
Well 21	170,000	166,000

BASE CASE MODEL RESULTS

As an additional calibration of the transport model, the concentration of TCE in Mill Creek was calculated based on model results and compared to the measured concentration. The model calculated concentration of 10 ug/L and 40 ug/L based on creek flows of 15 cfs (0.4 m^3/sec) and 3 cfs (0.08 m^3/sec), respectively, compared well with the creek TCE concentration of 15 ug/L measured in May, 1982 by EPA Region X.

The base case was defined as the 25-year simulation period from 1958 through 1983. Over this 25 year period, the model predicted that a total of 11,900 lb (5,400 Kg) of TCE were disposed of at the site and entered the groundwater flow system. Of this total, the model predicted that 5,790 lb (2,630 Kg) discharged to Mill Creek and the ditch, and 6,110 lb (2,770 Kg) remained in the flow system in the year 1983. Of the total mass leaving the system, about 95% discharges to Mill Creek and the remaining 5% discharges to the drainage ditch.

The distribution of TCE in the study area as predicted by the model at 5-year intervals is summarized in Table 5. The concentration in 1968 and 1978 are shown in Figures 19 and 20, respectively.

TABLE 5. DISTRIBUTION OF TCE IN THE MODEL BASE CASE SIMULATION

Year	TCE Inflow (lb)	TCE Outflow (lb)	TCE Remaining in Groundwater System (lb)
1963	2,975	525	2,455
1968	2,975	975	4,450
1973	2,975	1,335	6,095
1978	2,975	1,620	7,455
1983	0	1,335	6,110
Total	11,900	5,790	6,110

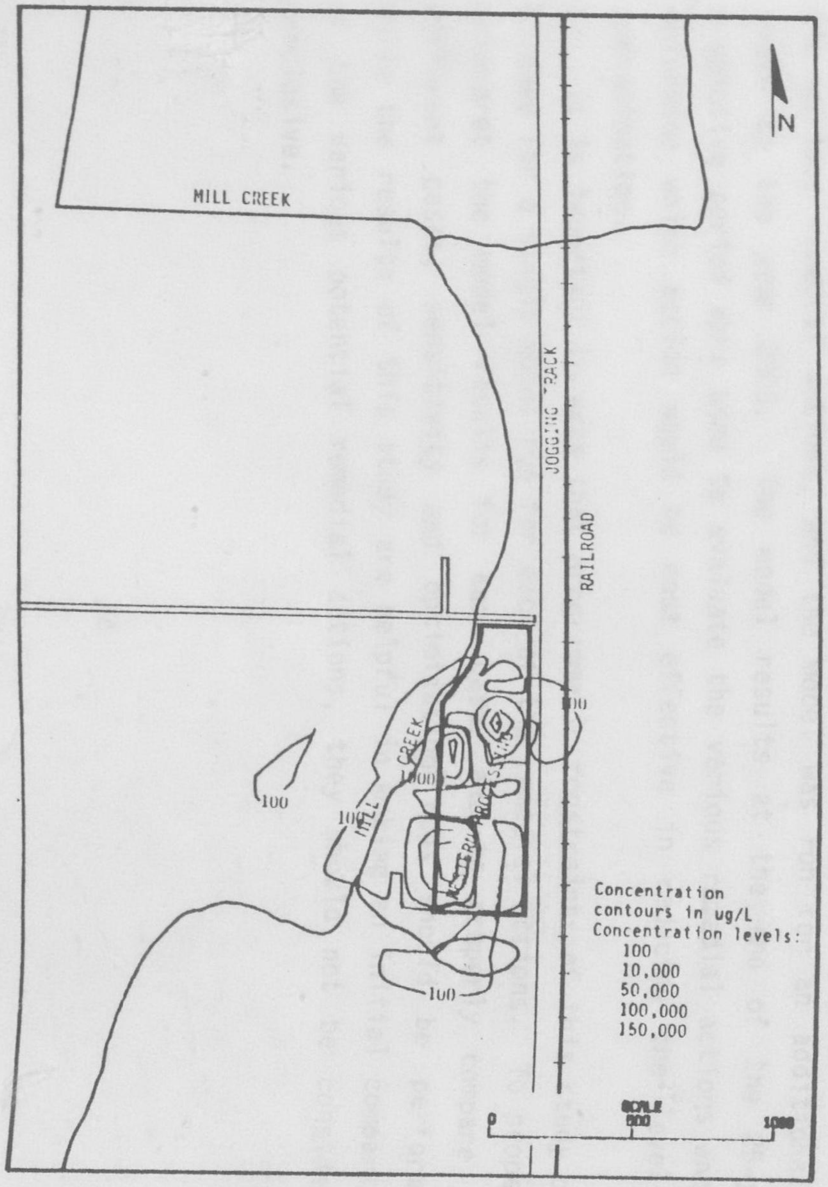

Figure 19. Model-Predicted 1968 Top of Layer 1 TCE Concentration Contours for the Base Case Simulation.

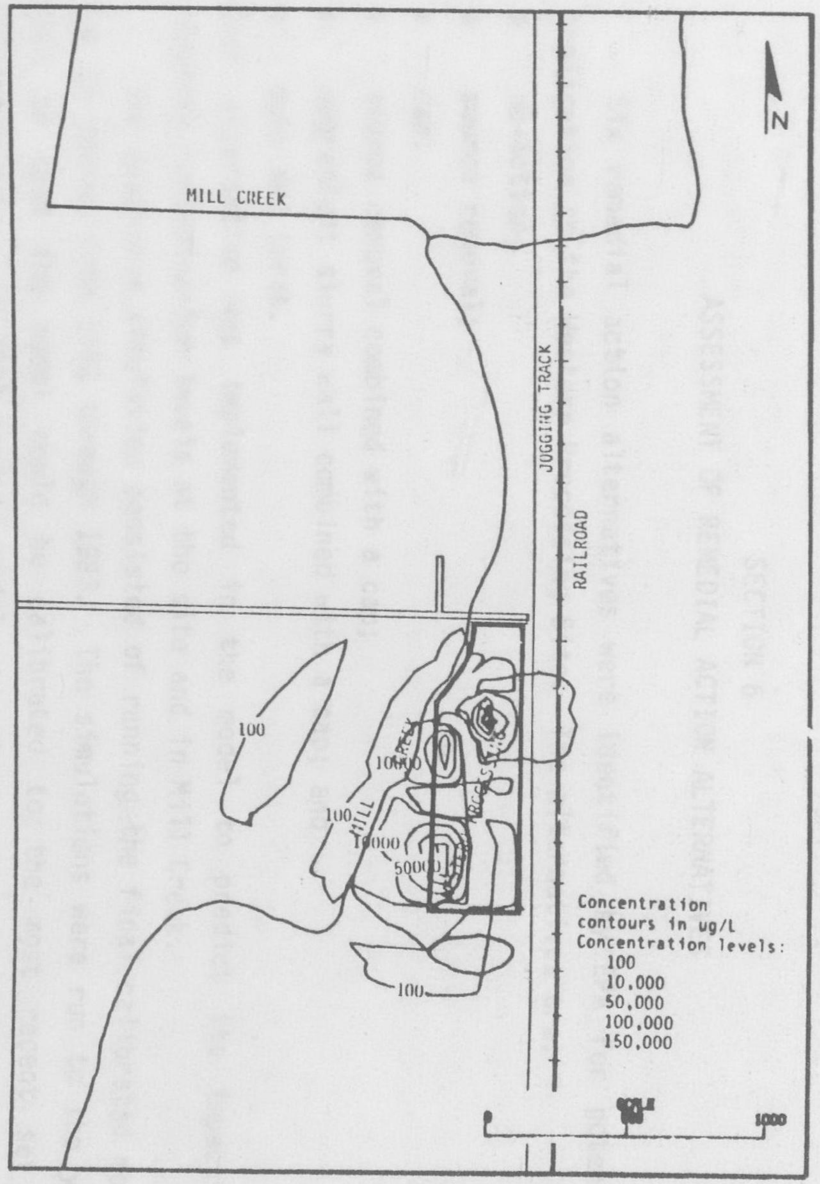

Figure 20. Model-Predicted 1978 Top of Layer 1 TCE Concentration Contours for the Base Case Simulation.

SECTION 6

ASSESSMENT OF REMEDIAL ACTION ALTERNATIVES

Six remedial action alternatives were identified by EPA for potential application to the Western Processing Site. The alternatives are:

- no-action;
- source removal;
- cap;
- source removal combined with a cap;
- upgradient slurry wall combined with a cap; and
- pump and treat.

Each alternative was implemented in the model to predict its impact on reducing contamination levels at the site and in Mill Creek.

The base-case simulation consisted of running the final calibrated model for 25 years, from 1958 through 1983. The simulations were run to the year 1983 so that the model could be calibrated to the most recent set of chemistry data. In 1983 certain model parameters were adjusted to simulate the various remedial actions, and the model was run for an additional 25 years to the year 2008. The model results at the end of the 25-year predictive period were used to evaluate the various remedial actions and to determine which action would be most effective in reducing the level of contamination.

It is important to note that programmatic constraints of this study only allowed for a single model run for each of the remedial actions. To properly interpret the model results for each case, and to properly compare the different cases, sensitivity and optimization runs should be performed. While the results of this study are helpful in making an initial comparison of the various potential remedial actions, they should not be considered conclusive.

ASSESSMENT APPROACH AND RESULTS

The six remedial actions simulated and how they were implemented in the model are discussed below. For each case, results are presented in the form of contour plots, maximum concentrations in the system, and total mass of TCE in the system and exiting the system.

No-Action

The first step in the remedial action analysis was to simulate the no-action scenario to establish a benchmark against which all other actions could be compared. The no-action scenario entailed running the final calibrated model (base case) 25 years into the future (1984 through 2008) without any changes. The model simulated the continued migration of the TCE which entered the flow system in the base case simulation.

TCE concentration contours at the top of Layer 1 in the years 1988, 1998, and 2008 for the no-action case are shown in Figures 21, 22, and 23, respectively. The maximum TCE concentrations in the groundwater at each of the three source areas in the year 2008 are listed in Table 6. The total mass of TCE in the flow system, and the total mass discharging to Mill Creek and the ditch at 5-year time intervals are shown in Table 7. Table 7 shows that of the 11,900 lb (5,400 Kg) that entered the flow system between 1958 and 1983, 20% (2,375 lb (1,075 Kg)) remains in the system in the year 2008. Of the 6,110 lb (2,770 Kg) of TCE remaining in the flow system in 1983, about 60% (3,790 lb (1,720 Kg)) exited to Mill Creek and the ditch by the year 2008. As in the base case, of the amount exiting the groundwater flow system about 95% entered Mill Creek and the remaining 5% entered the drainage ditch.

TABLE 6. MODEL PREDICTED MAXIMUM CONCENTRATION (ug/L) IN THE GROUNDWATER AT THE THREE SOURCE AREAS IN THE YEAR 2008 FOR THE REMEDIAL ACTION SIMULATIONS

	No-Action	Source Removal	Cap	Source Removal and Cap	Slurry Wall and Cap	Pump and Treat
Reaction Pond I	21,000	810	50,810	1,590	13,415	260
Reaction Pond III	770	330	2,545	630	480	580
Well 21	17,000	2,400	52,740	4,365	12,055	1,990

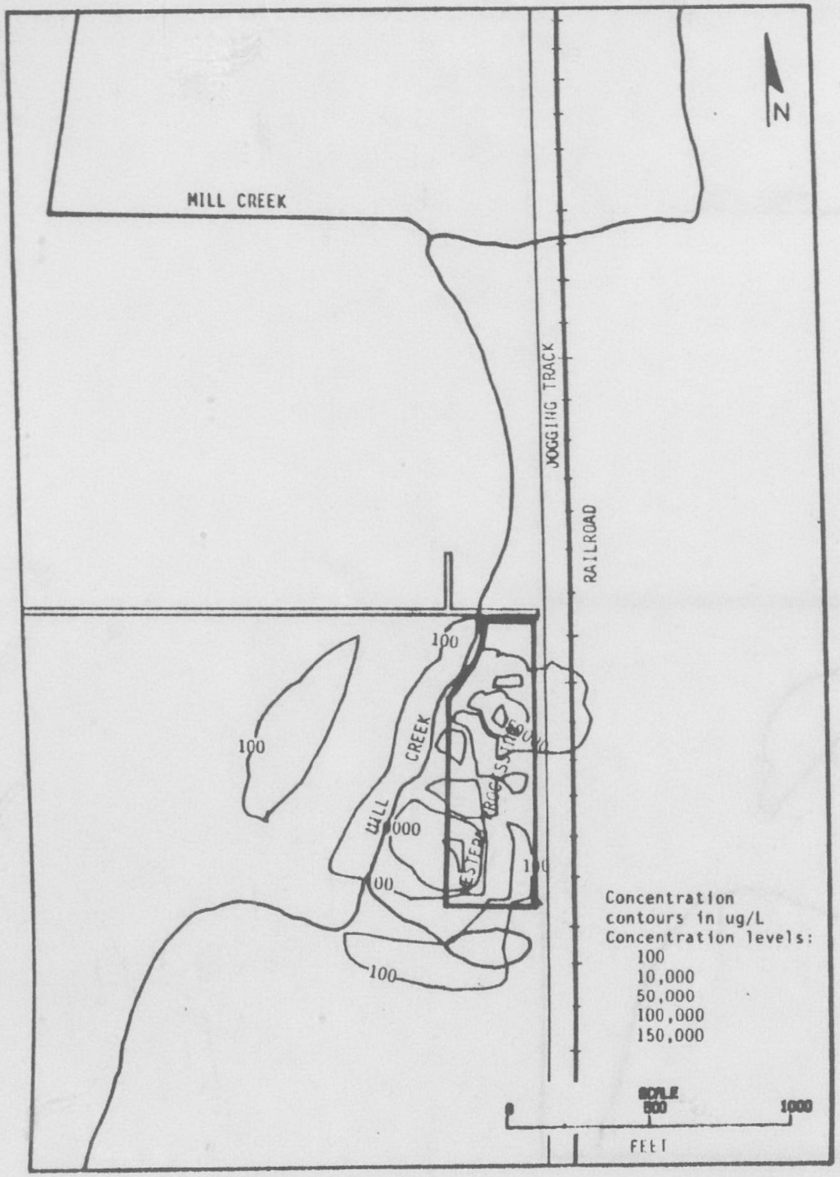

Figure 21. Model-Predicted 1988 Top of Layer 1 TCE Concentration Contours for the No-Action Simulation.

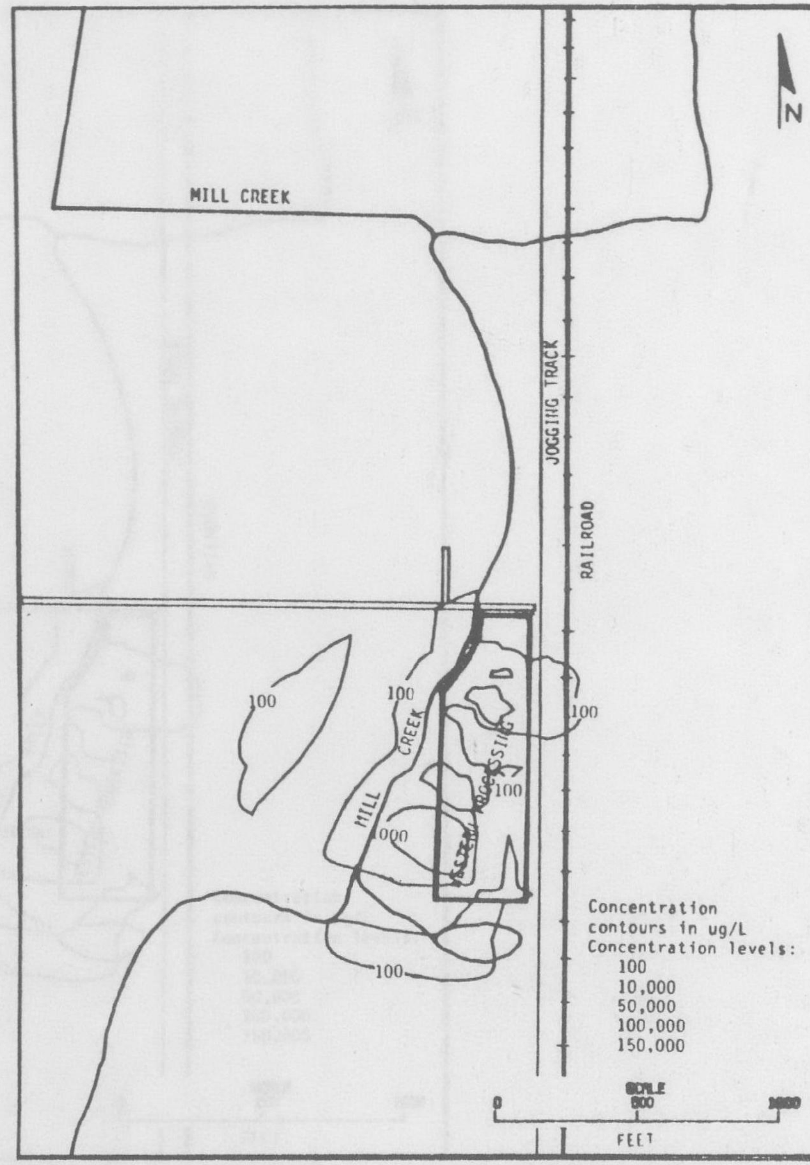

Figure 22. Model-Predicted 1998 Top of Layer 1 TCE Concentration Contours for the No-Action Simulation.

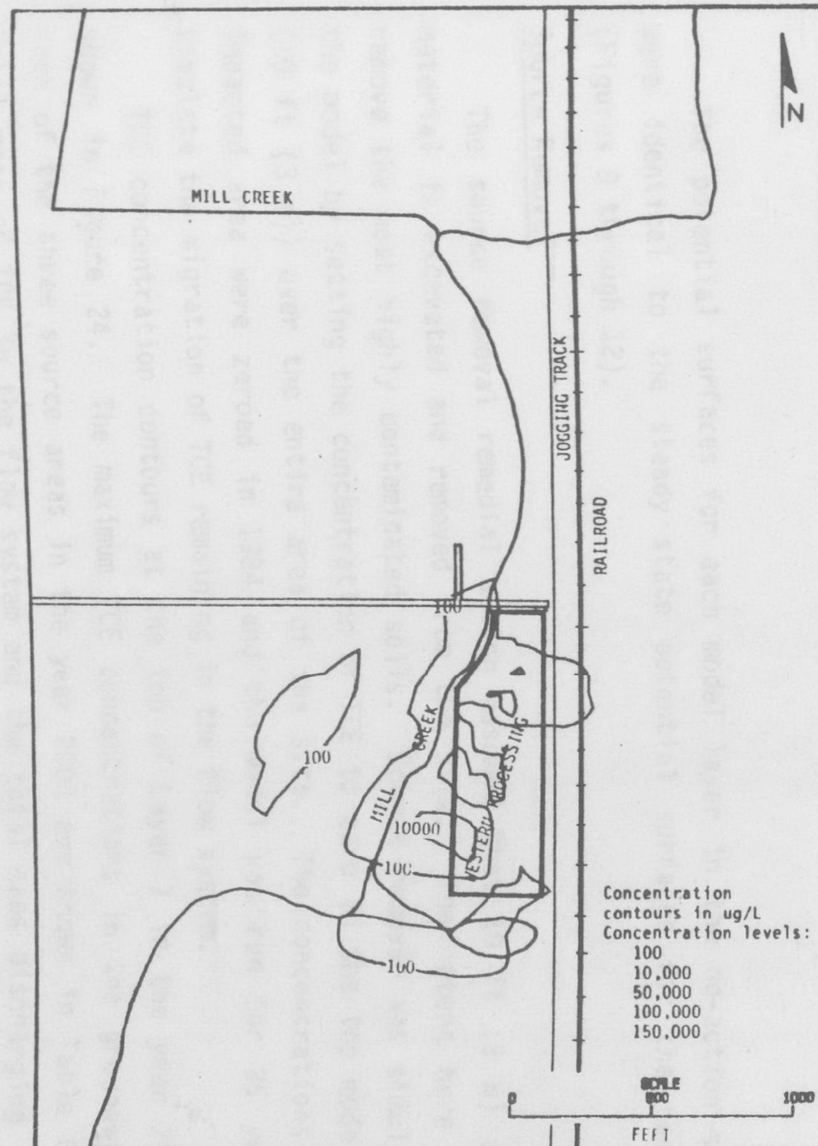

Figure 23. Model-Predicted 2008 Top of Layer 1 TCE Concentration Contours for the No-Action Simulation.

TABLE 7. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE NO-ACTION SIMULATIONS

Year	TCE Inflow (lb)	TCE Outflow (lb)	Total Mass in System (lb)
1988	0	1,075	5,055
1993	0	880	4,180
1998	0	730	3,460
2003	0	605	2,865
2008	0	500	2,375
Total	0	3,790	

The potential surfaces for each model layer in the no-action scenario were identical to the steady state potential surfaces for the base case (Figures 8 through 12).

Source Removal

The source removal remedial action assumed that 10 ft (3 m) of fill material is excavated and removed from the site. The intent here was to remove the most highly contaminated soils. Source removal was simulated in the model by setting the concentration of TCE to zero in the top model layer (10 ft (3 m)) over the entire area of the site. The concentrations in the impacted area were zeroed in 1984 and the model was run for 25 years to simulate the migration of TCE remaining in the flow system.

TCE concentration contours at the top of Layer 1 in the year 2008 are shown in Figure 24. The maximum TCE concentrations in the groundwater at each of the three source areas in the year 2008 are shown in Table 6. The total mass of TCE in the flow system and the total mass discharging to Mill Creek and the ditch at 5-year intervals are shown in Table 8. Table 8 shows that a total of 2,425 lb (1,100 Kg) of TCE exited the flow system to Mill Creek and the ditch over the 25 year period, and that 1,315 lb (595 Kg) remains in the flow system in the year 2008.

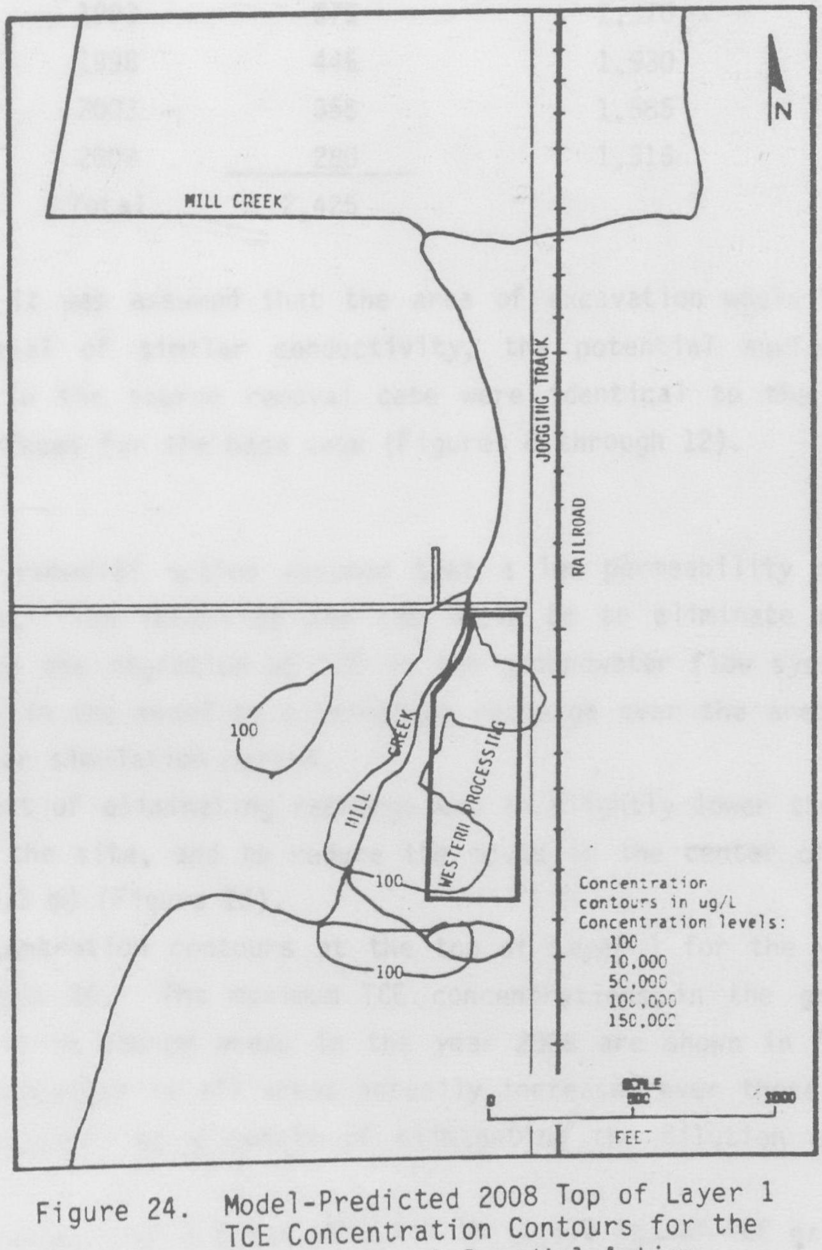

Figure 24. Model-Predicted 2008 Top of Layer 1 TCE Concentration Contours for the Source Removal Remedial Action Simulation.

TABLE 8. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE SOURCE REMOVAL REMEDIAL ACTION

Year	TCE Outflow (lb)	Total Mass of TCE in System (lb)
1988	770	2,935
1993	575	2,370
1998	445	1,930
2003	355	1,585
2008	280	1,315
Total	2,425	

Because it was assumed that the area of excavation would be backfilled with a material of similar conductivity, the potential surfaces for each model layer in the source removal case were identical to the steady state potential surfaces for the base case (Figures 8 through 12).

Cap

The cap remedial action assumed that a low permeability cap is placed over the site. The intent of the cap would be to eliminate recharge, and thereby reduce the migration of TCE in the groundwater flow system. The cap was simulated in the model by eliminating recharge over the area of the site for the 25-year simulation period.

The effect of eliminating recharge was to slightly lower the water table over most of the site, and to reduce the mound in the center of the site by about 1 ft (0.3 m) (Figure 25).

TCE concentration contours at the top of Layer 1 for the year 2008 are shown in Figure 26. The maximum TCE concentrations in the groundwater at each of the three source areas in the year 2008 are shown in Table 6. The maximum concentration in all areas actually increased over those predicted by the no-action case, as a result of eliminating the dilution effect of the recharge.

Table 9 shows that a total of 3,475 lb (1,575 Kg) of TCE exited the flow system to Mill Creek and the ditch over the 25-year simulation, and that 2,690 lb (1,200 Kg) remains in the flow system in the year 2008.

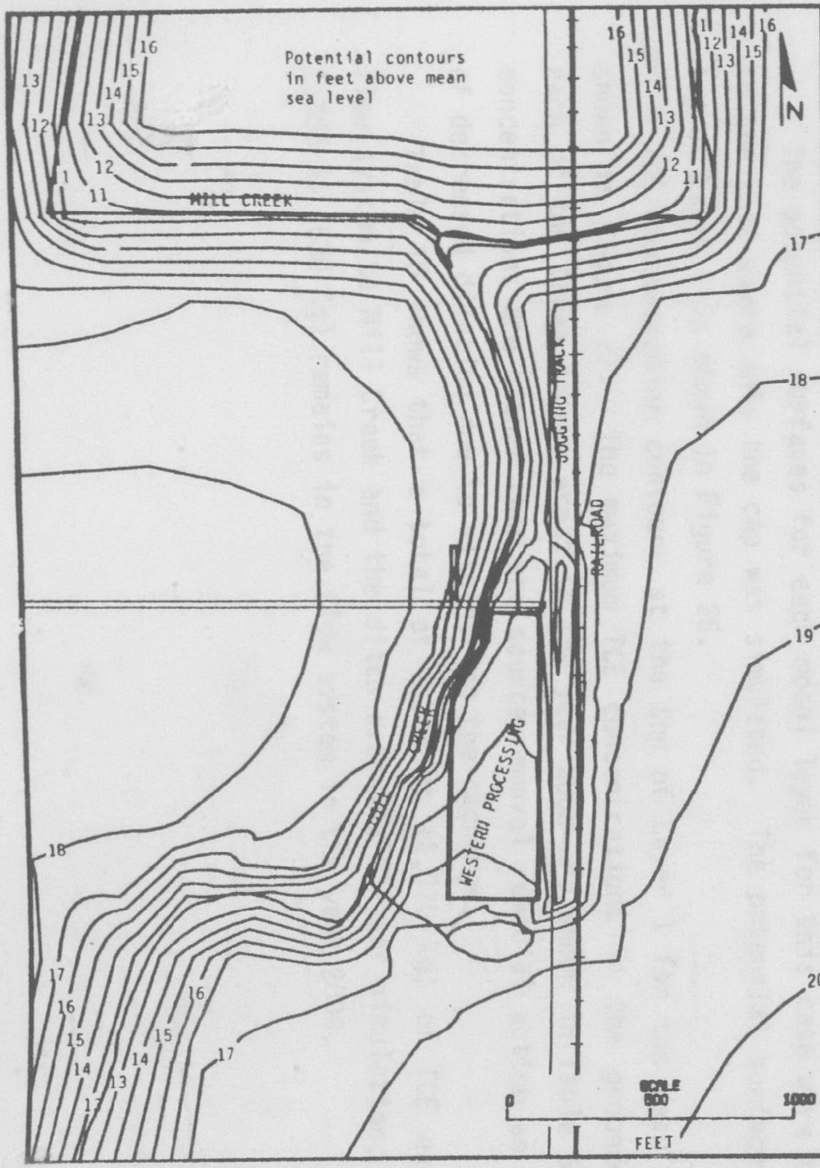

Figure 25. Model-Predicted Top of Layer 1 Potential Surface for the Cap Remedial Action Simulation.

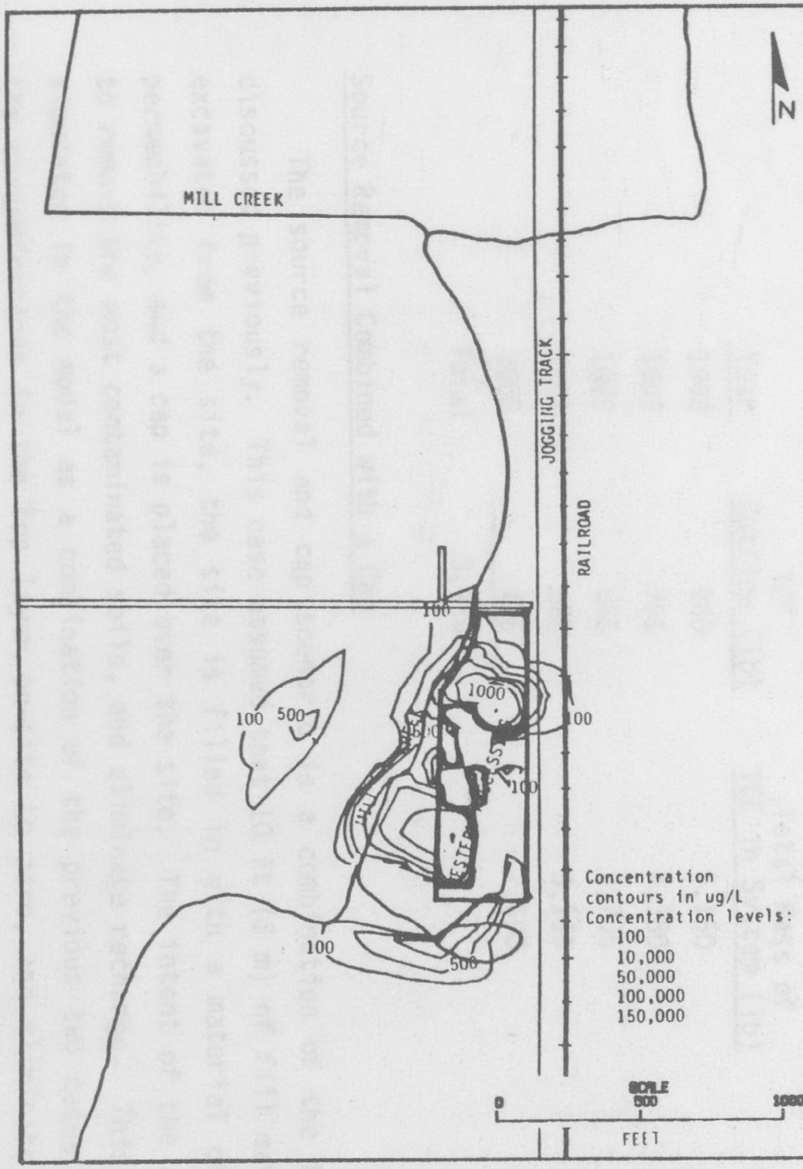

Figure 26. Model-Predicted 2008 Top of Layer 1 TCE Concentration Contours for the Cap Remedial Action Simualtion.

TABLE 9. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE CAP REMEDIAL ACTION

Year	TCF Outflow (lb)	Total Mass of TCE in System (lb)
1988	980	5,150
1993	795	4,360
1998	665	3,705
2003	560	3,155
2008	475	2,690
Total	3,475	

Source Removal Combined with a Cap

The source removal and cap scenario is a combination of the two cases discussed previously. This case assumed that 10 ft (3 m) of fill material is excavated from the site, the site is filled in with a material of similar permeability, and a cap is placed over the site. The intent of the action is to remove the most contaminated soils, and eliminate recharge. This case was simulated in the model as a combination of the previous two cases: reduce the concentrations in the top layer on-site to zero, and eliminate recharge at the site.

The potential surfaces for each model layer for this case were identical to the case where only the cap was simulated. The potential surface for the top of Layer 1 is shown in Figure 25.

TCE concentration contours at the top of Layer 1 for the year 2008 are shown in Figure 27. The maximum TCE concentrations in the groundwater at each of the three source areas in the year 2008 are shown in Table 6. These concentrations are higher than the source removal remedial action as a result of decreased dilution due to eliminating the recharge.

Table 10 shows that a total of 2,355 lb (1,070 Kg) of TCE exited the flow system to Mill Creek and the ditch over the 25-year simulation, and that 1,385 lb (630 Kg) remains in the flow system in the year 2008.

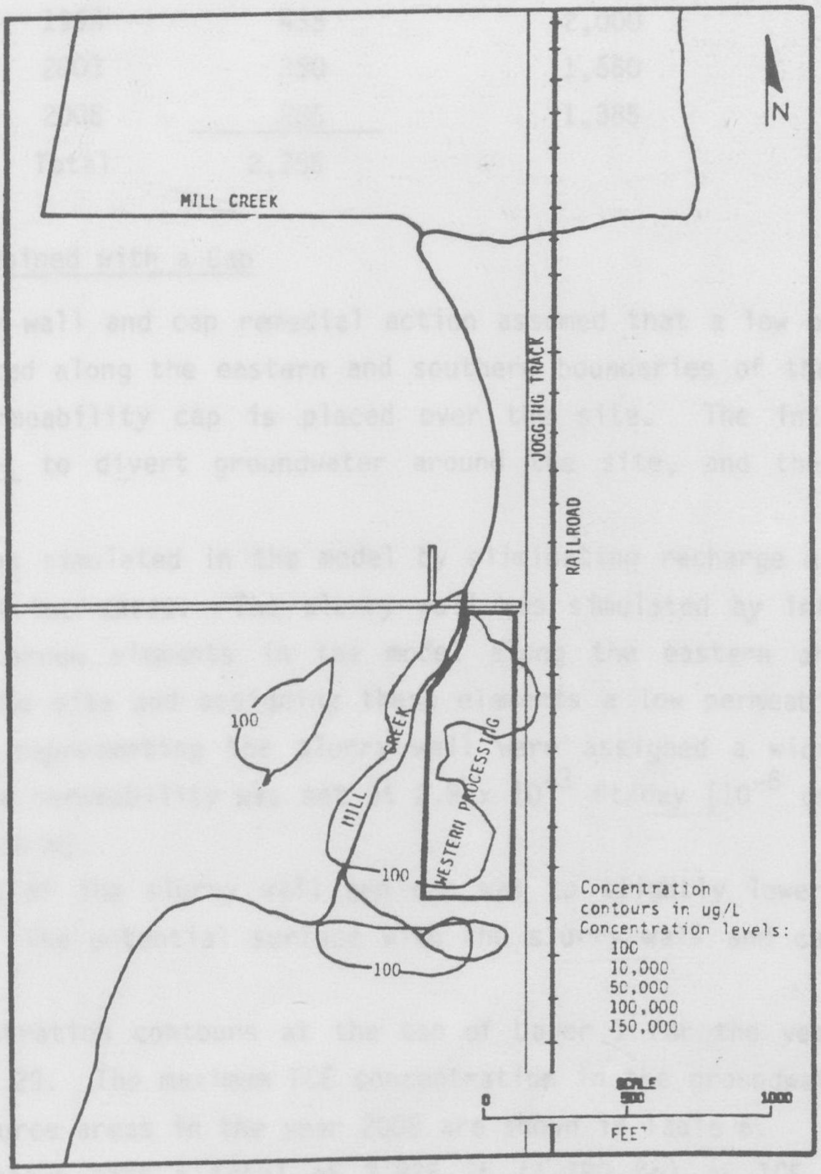

Figure 27. Model-Predicted 2008 Top of Layer 1 TCE Concentration Contours for the Source Removal Plus Cap Remedial Action Simulation.

TABLE 10. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE SOURCE REMOVAL PLUS CAP REMEDIAL ACTION

Year	TCE Outflow (lb)	Total Mass of TCE in System (lb)
1988	735	2,975
1993	550	2,430
1998	435	2,000
2003	350	1,660
2008	285	1,385
Total	2,355	

Slurry Wall Combined with a Cap

The slurry wall and cap remedial action assumed that a low permeability barrier is placed along the eastern and southern boundaries of the site, and that a low permeability cap is placed over the site. The intent of the slurry wall was to divert groundwater around the site, and the cap would reduce recharge.

The cap was simulated in the model by eliminating recharge as discussed in the previous two cases. The slurry wall was simulated by introducing a row of long, narrow elements in the model along the eastern and southern boundaries of the site and assigning these elements a low permeability. The model elements representing the slurry wall were assigned a width of 5 ft (1.5 m), and the permeability was set at 2.8 x 10^{-3} ft/day (10^{-6} cm/sec) to a depth of 30 ft (9 m).

The effect of the slurry wall and cap was to slightly lower the water table on site. The potential surface with the slurry wall and cap is shown in Figure 28.

TCE concentration contours at the top of Layer 1 for the year 2008 are shown in Figure 29. The maximum TCE concentration in the groundwater at each of the three source areas in the year 2008 are shown in Table 6.

Table 11 shows that a total of 3,925 lb (1,780 Kg) of TCE exited the flow system to Mill Creek and the ditch over the 25-year simulation, and that 2,240 lb (1,015 Kg) remains in the flow system in the year 2008.

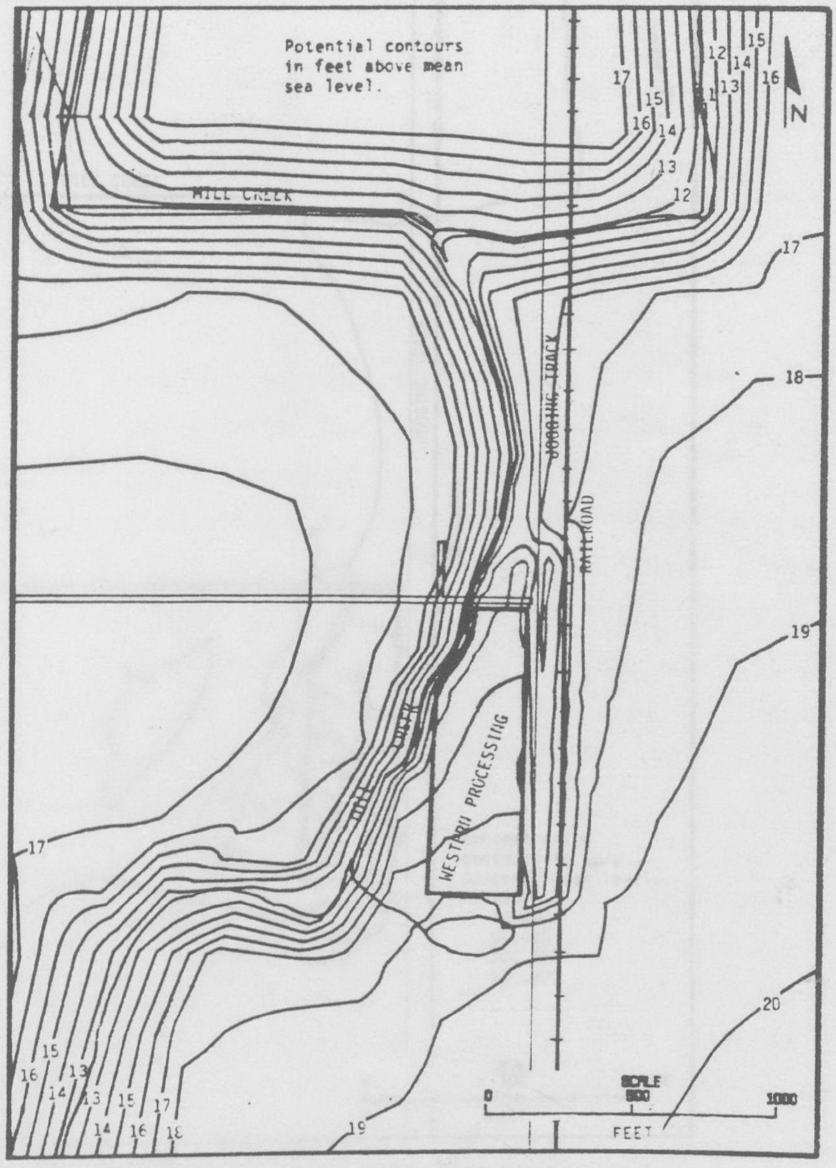

Figure 28. Model-Predicted Top of Layer 1 Potential Surface for the Slurry Wall Plus Cap Remedial Action Simulation.

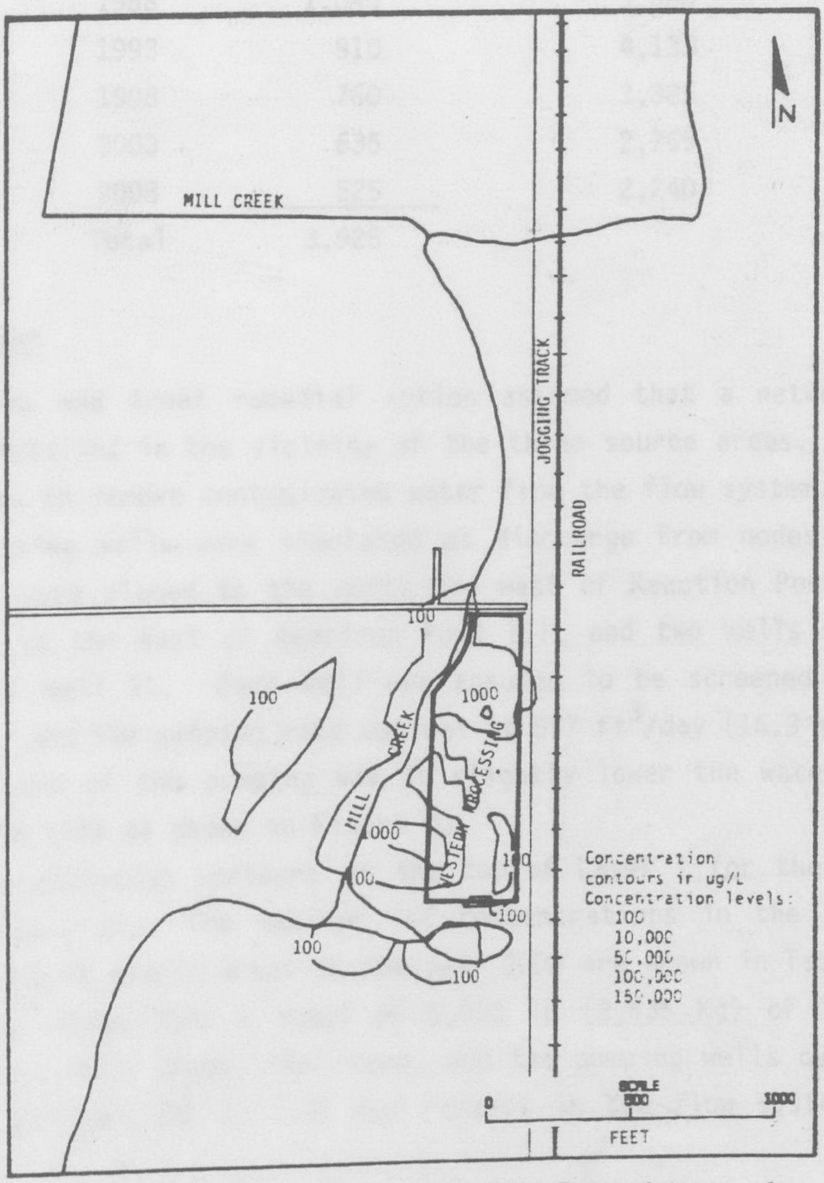

Figure 29. Model-Predicted 2008 Top of Layer 1 TCE Concentration Contours for the Slurry Wall Plus Cap Remedial Action Simulation.

TABLE 11. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE SLURRY WALL PLUS CAP REMEDIAL ACTION

Year	TCE Outflow (lb)	Total Mass of TCE in System (lb)
1988	1,095	5,040
1993	910	4,135
1998	760	3,385
2003	635	2,755
2008	525	2,240
Total	3,925	

Pump and Treat

The pump and treat remedial action assumed that a network of pumping wells was installed in the vicinity of the three source areas. The intent of the wells was to remove contaminated water from the flow system.

The pumping wells were simulated as discharge from nodes in the model. Three wells were placed to the north and west of Reaction Pond I, two wells were placed to the east of Reaction Pond III, and two wells were placed to the north of Well 21. Each well was assumed to be screened to a depth of 30 ft (9 m), and the pumping rate was set at 577 ft^3/day (16.3 m^3/day).

The effect of the pumping was to slightly lower the water table in the center of the site as shown in Figure 30.

TCE concentration contours at the top of Layer 1 for the year 2008 are shown in Figure 31. The maximum TCE concentrations in the groundwater at each of the three source areas in the year 2008 are shown in Table 6.

Table 12 shows that a total of 5,810 lb (2,635 Kg) of TCE exited the flow system to Mill Creek, the ditch, and the pumping wells over the 25-year simulation and that 330 lb (150 Kg) remains in the flow system in the year 2008.

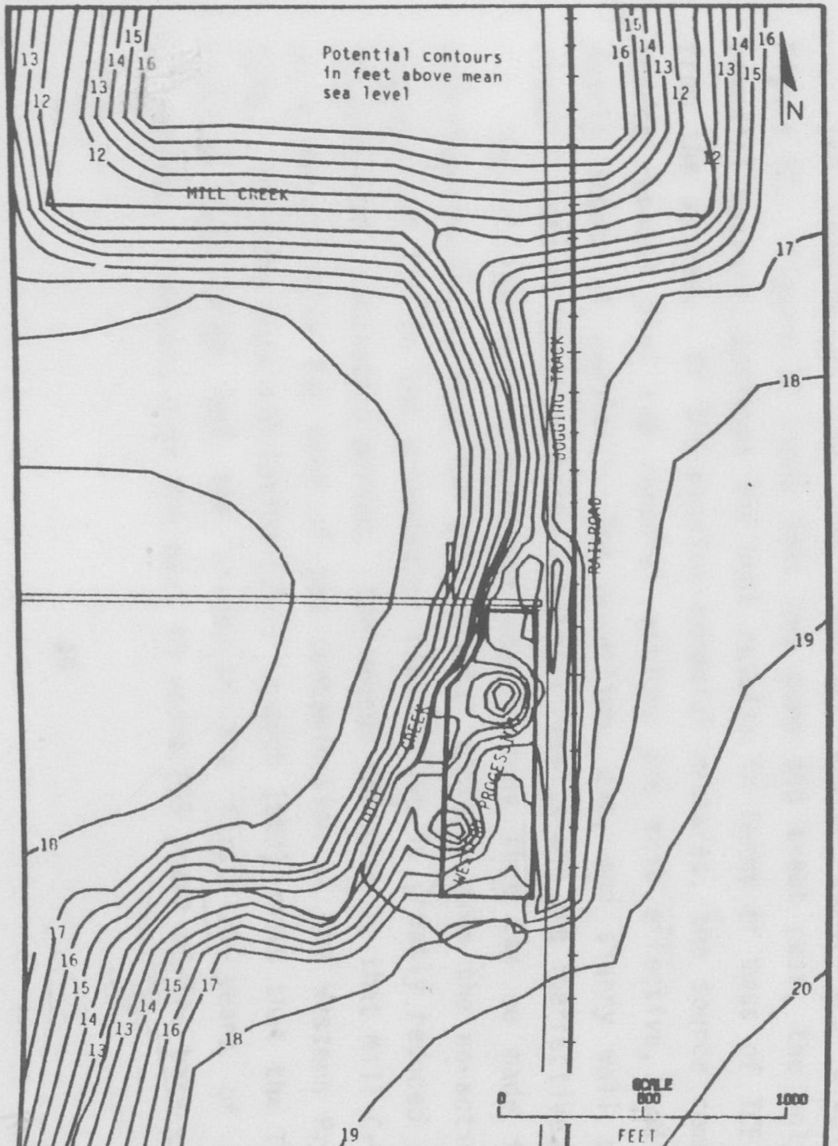

Figure 30. Model-Predicted Top of Layer 1 Potential Surface for the Pump and Treat Remedial Action Simulation.

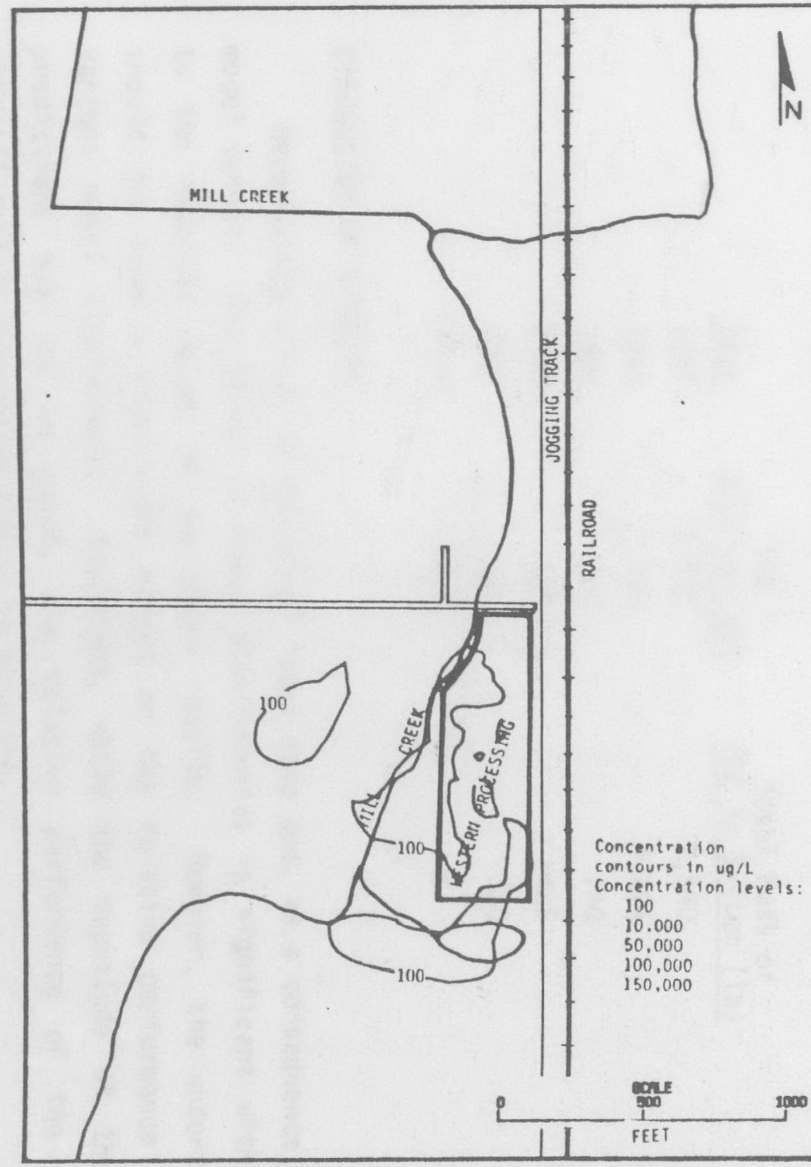

Figure 31. Model-Predicted 2008 Top of Layer 1 TCE Concentration Contours for the Pump and Treat Remedial Action Simulation.

TABLE 12. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE PUMP AND TREAT REMEDIAL ACTION

Year	TCE Outflow (lb)	Total Mass of TCE in System (lb)
1988	3,550	2,540
1993	1,260	1,295
1998	565	740
2003	285	465
2008	150	330
Total	5,810	

DISCUSSION OF RESULTS

Uncertainty exists in the model input data and, as a consequence, in the model output. The effect of these uncertainties is significant with regard to the absolute values of the model results. However, the uncertainties should not have a significant effect on the relative performance of the various model simulations. Therefore, while the magnitude of the model predictions may not be exact, the relative performance of the various remedial actions considered should be accurate.

The results of the five remedial action cases are displayed in Figure 32. Figure 32 shows that the pump and treat case, the only active remedial measure, achieves the best results in terms of mass of TCE removed from the system. Of the passive remedial measures, the source removal and source removal plus cap remedial actions are most effective, and achieve nearly identical results. The no-action, cap, and slurry wall plus cap remedial actions achieve nearly identical results and are ineffective.

One of the most significant observations that can be made from the modeling results is that for all remedial actions, even the no-action case, the mass of TCE in the groundwater flow system is greatly reduced over the 50-year model simulation period. The reason for this is that Mill Creek acts as a natural sink for most of the contamination at the Western Processing Site. The base case simulation (1958 through 1983) shows that the TCE plume reaches Mill Creek and the ditch in the first 10 years of disposal operations. However, over the next 40 years (15 years of the base case plus

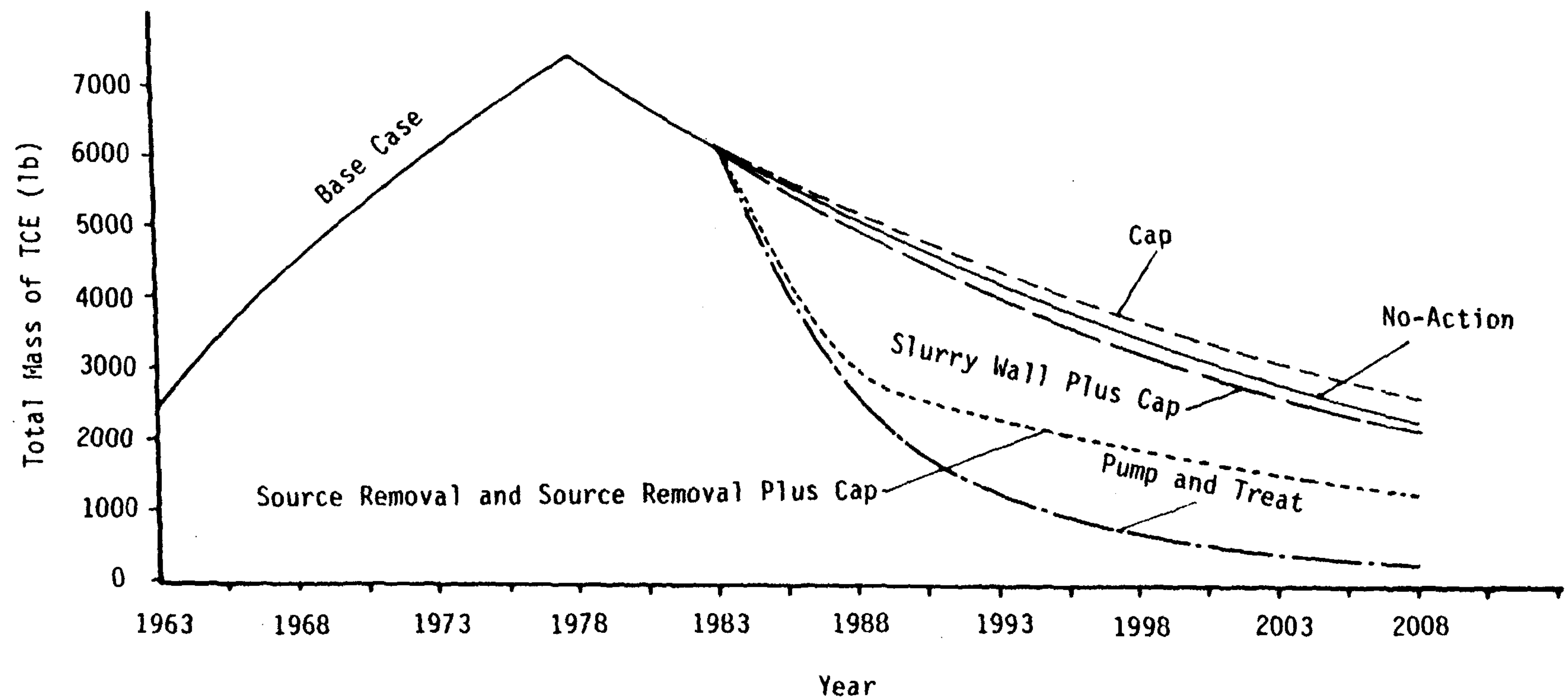

Figure 32. Comparison of the Total Mass of TCE Remaining in the Groundwater System for the Five Remedial Action Cases.

the no-action case), the plume advances only slightly and the majority of the mass of TCE in the system discharges to Mill Creek. For the base case, the model predicted that almost half of the TCE that entered the system has already exited the system by 1983. In the no-action simulation (1984 through 2008), the model predicted that about 80% of the TCE that entered the system has exited by the year 2008. Of the amount of TCE exiting the system, the model predicted that the majority of it (95%) entered Mill Creek while only 5% entered the drainage ditch.

The cap and slurry wall plus cap remedial actions show a similar trend to that for the no-action case. While these cases alter the distribution of TCE slightly, about 80% of the TCE in the system still discharges to Mill Creek by the year 2008.

The caps in both of these cases have virtually no effect because the leaching of TCE into the flow system was not simulated in the model past 1978. Therefore, eliminating the recharge, as was done to simulate a cap, had no effect on reducing the amount of TCE entering the system. The cap did slightly alter the groundwater flow pattern and actually slightly increased the mass of TCE exiting to Mill Creek.

The assumption that TCE is leaching into the groundwater only during the period of active disposal is questionable. This assumption was based on the fact that the water table is very near the surface (about 5 ft (2 m)), and that initial remedial measures have already been performed at the site. This assumption needs to be studied further before categorically ruling out the benefits of a cap at the site.

The model predicted that the source removal action would remove about 3,000 lb (1,360 Kg) of TCE from the system. Once that initial mass is removed, the mass remaining in the system discharges to Mill Creek at a similar rate as in the no-action case. By the year 2008, about 90% of the total mass of TCE that entered the groundwater during disposal will have exited the system. Of the 6,000 lb (2,720 Kg) remaining in the system in 1983, about half of it was removed by excavation, 25% discharged to Mill Creek and 25% remains in the system by the year 2008.

The pump and treat action removed about 2,500 lb (1,135 Kg) of TCE in the first 5 years (1983 through 1988) in addition to the 1,000 lb (450 Kg) that discharges to Mill Creek. After the first 5 years the mass of TCE removed by the wells rapidly decreases because the concentration of TCE in the withdrawn groundwater decreases. By the year 2008, 95% of the TCE remaining in the flow system in 1983 will have exited.

SECTION 7

SIMPLIFIED ANALYTICAL APPROACH TO THE WESTERN PROCESSING DATA SET

The objectives of this subtask were to: 1) reformat the data used in the CFEST model of the Western Processing Site to a form that lends itself to simple analytical solutions; and 2) use simple analytical techniques to predict hydraulic response at the site to remedial action alternatives. The various remedial action alternatives that are appropriate for the site are no-action, pump and treat, slurry wall with cap, source removal, and capping. Remedial Action Modeling Volume 2, Simplified Methods for Subsurface and Waste Control Actions (Brown, 1984), provided a compendium of analytical solutions that may be appropriate for various remedial actions. Most of the analytical solutions discussed in the report are appropriate for simple rather than complex groundwater systems. Solutions were listed for remedial actions similar to those proposed for the Western Processing Site. Given the complex layering and hydrology of the site, only the pump and treat option was analyzed with the simplified analytical solution.

PUMPING ANALYSIS

The CFEST model requires values for hydraulic conductivity (vertical and horizontal), aquifer thicknesses, gradients, recharge, porosity and storage in order to predict groundwater flow direction and velocity. The effects of anisotropy and other inhomogeneities can be included in the model. Simple analytical solutions are limited to smaller, less complicated data sets. The analytical program compared to the CFEST model could not calculate the effects of multiple layers, inhomogeneities, recharge, or variable thickness. The calculator solutions were designed to handle simple systems or systems where limited data are available. The computer models like CFEST can handle large data sets and very complex hydrologic relationships.

Several hand-held calculator programs for well hydraulics were identified in Brown (1984). The Theis condition well field program, NWELLS, which can be used to determine the effect of pumping and/or recharge on an aquifer (van der Heidje, 1983) was chosen as the most suitable analytical program to analyze the data set used for the Western Processing Site. The NWELLS program uses the Theis equation to determine the drawdown at a well for a given set of conditions and sums the results for an observation well. All calculations were performed on a Hewlett-Packard 41-CV hand-held programmable calculator.

Many factors influence the groundwater flow patterns at the Western Processing Site. A shallow groundwater system intersects the surface along the west side of the site at Mill Creek. A groundwater/surface water interface also occurs at the drainage ditch along the east side of the site. A groundwater mound has been identified near the center of the site, and a portion of the site has already been covered by an impermeable cap.

The pump and treat remedial action tested in the CFEST model was used to guide the analytical program. The seven dewatering wells simulated in the CFEST model were set up on a grid, and X-Y coordinates were determined for the NWELLS program (Figure 33). The first 5 analytical simulations used a hydraulic conductivity which was initially (before calibration) thought to be representative of the surface materials on site (28.3 ft/day (8.6 m/day)). The depths of the 7 withdrawal wells were 30 ft (9.2 m), the same as in the CFEST model. The drawdown at a single well (the observation well in Figure 33) as predicted by the analytical solution was compared to the drawdown at the same location as predicted by the CFEST model. A summary of the input parameters for the analytical calculation are shown in Table 13.

The first analytical runs were used to help determine a reasonable pumping rate for the CFEST model. A pumping rate of 30 gpm (113 L/min) resulted in a drawdown greater than the thickness of the aquifer. A pumping rate of 10 gpm (38 L/min) (Case 6, Table 13) predicted a composite drawdown of 19.8 ft (6.0 m), a reasonable range for the Western Processing Site.

After calibration of the CFEST model it was determined that the most reasonable hydraulic conductivity for the sand and gravel layer was 2.5 ft/day (0.8 m/day), which corresponds to a transmissivity of 75 ft^2/day (7.0 m^m/day). This transmissivity was used in all subsequent analytical calculations (Cases 7 through 13).

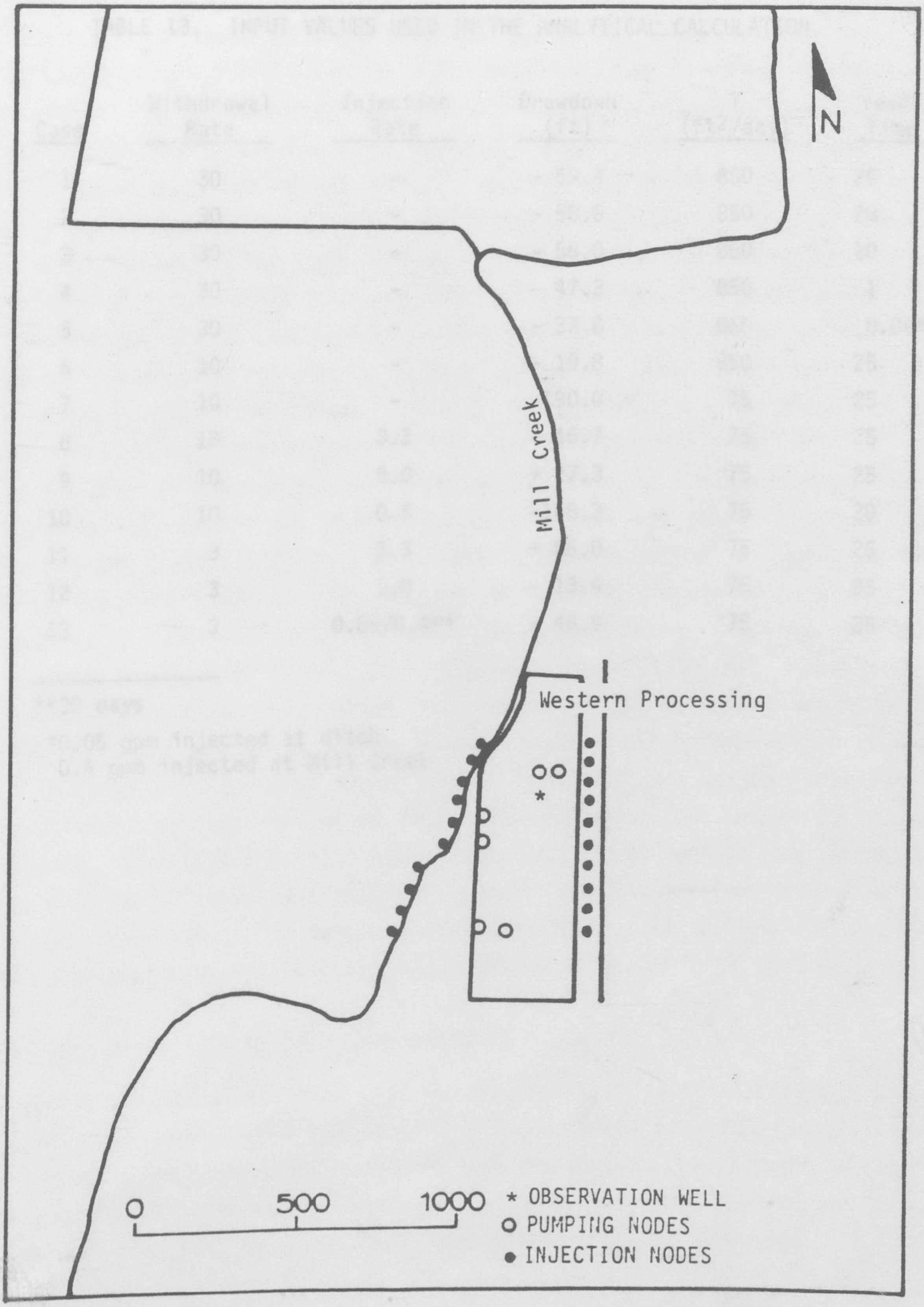

Figure 33. Location Map of Pumping and Injection Wells Used in the Analytical Solution.

TABLE 13. INPUT VALUES USED IN THE ANALYTICAL CALCULATION.

Case	Withdrawal Rate	Injection Rate	Drawdown (ft)	T (ft^2/day)	Years Time
1	30	-	- 59.4	850	25
2	30	-	- 58.6	850	20
3	30	-	- 56.0	850	10
4	30	-	- 47.3	850	1
5	30	-	- 37.8	850	0.08*
6	10	-	- 19.8	850	25
7	10	-	-190.0	75	25
8	10	3.3	- 46.7	75	25
9	10	5.0	+ 27.3	75	25
10	10	0.5	-168.3	75	20
11	3	3.3	+ 86.0	75	25
12	3	1.0	- 13.4	75	25
13	3	0.05/0.4**	- 46.9	75	25

**30 days

*0.05 gpm injected at ditch
0.4 gpm injected at Mill Creek

Case 7 in Table 13 shows that the drawdown calculated using the 10 gpm (38 L/min) pumping rate with the lower transmissivity value was calculated to be 190 ft (58 m), obviously too large a value. A review of the CFEST data showed that the creek discharge decreased slightly once the remedial action wells began pumping. Based on this observation, a series of 20 injection wells were sited along the creek and ditch to the east and west of the site to simulate recharge to the surface aquifer. Three runs were made varying the rate of injection at each well from 5.0 to 0.5 gpm (19 to 2 L/min). Case 9 showed that the potentiometric surface rose above the ground surface if 5.0 gpm (19 L/min) were injected at each of the wells. The other injection rates resulted in too much drawdown. Case 11 was run with a withdrawal rate of 3 gpm (11.3 L/min) per pumping well, and an injection rate of 3.3 gpm (12.5 L/min) at each creek and ditch well. Case 12 was similar but had an injection rate of 1.0 gpm (3.8 L/min) at the creek and ditch injection nodes. The 3.3 gpm (12.5 L/min) injection rate raised the surface of the water table above the land surface. The 1.0 gpm (3.8 L/min) injection rate created a drawdown of 13.4 ft (4.1 m) which was the closest match to the CFEST predicted drawdown of 10.5 ft (3.2 m) with a 3 gpm (11.3 L/min) pumping rate.

The CFEST model runs showed that about 4.5 gpm (17 L/min) would be lost from the creek and ditch if the remedial action wells were pumped at 3 gpm (11.3 L/min). The creek would account for about 95% of the loss and the ditch would account for about 5%. Case 13 shows the analytical program solution using a 3 gpm (11.3 L/min) pumping rate at each of the wells, 0.05 gpm (0.2 L/min) injected at each ditch well, and 0.4 gpm (1.5 L/min) injected at each creek well. The predicted drawdown of 46.9 ft (14.3 m) is about five times greater than the 10.5 ft (3.2 m) predicted by the CFEST model.

ANALYSIS OF THE ANALYTICAL PROGRAM RESULTS

The analytical solution used on the hand-held calculator proved to be a useful tool when used in conjunction with the CFEST code for remedial action analysis. The calculator could be used to predict the effects of various pumping rates before model runs were made so that the modeler could avoid some of the scaling runs that are often required prior to choosing a particular pumping rate. In this task, the hand-held calculator program showed that both the 30 gpm (113 L/min) and the 10 gpm (38 L/min) withdrawal rates caused excessive drawdowns before running CFEST.

For this study, the analytical program was used in conjunction with the model. The input parameters used in the program were taken from the model calibration runs rather than from the raw field data. The interaction between the hand-held calculator and the CFEST model was complementary. The model could take into account the effects of a multi-layered anisotropic system, and the calculator could be used to make estimates of the model response given the calibrated parameters from the model.

The hand-held calculator program was helpful when used in conjunction with CFEST but it is not adequate for independent solutions of a problem such as the one at the Western Processing Site. The effects of surface water bodies could only be estimated and the effects of the multi-layered aquifers could not be duplicated. The CFEST predicted drawdown from the remedial action wells could be duplicated, but only with what is believed to be an unrealistic injection rate at the creek and ditch. The final analytical solution to the problem using the calibrated CFEST parameters resulted in over 46 ft of drawdown, greater than the thickness of the aquifer being pumped.

The analytical solutions are suitable for evaluating simple hydrologic systems or systems where limited data require simplifying assumptions. Complex models like CFEST are more appropriate for handling complex data sets (i.e., multiple hydrostratigraphic layers with different hydraulic conductivities and porosities, stream/aquifer interactions, variable depths of pumping wells, etc.) such as exists at the Western Processing Site.

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APPENDIX A

RECHARGE CALCULATIONS

Recharge due to precipitation was calculated using the water balance formula:

$$\text{Recharge} = \text{Precipitation} - \text{Actual Evaporation} - \text{Runoff} \qquad \text{(A-1)}$$

Average annual precipitation and actual evapotranspiration for the study area are about 39 in./yr (99 cm/yr) and 18 in./yr (46 cm/yr), respectively (NOAA, 1974). Runoff was calculated using a method developed by the U.S. Soil Conservation Service and modified by Dunne and Leopold (1978). The technique is based on a simplified infiltration model of runoff, daily precipitation events, and empirical approximations which consider such factors as soil type, land use, vegetative cover, and storm separation interval to determine the antecedent soil moisture conditions.

A program developed at Battelle and based on the Soil Conservation Service method was used to calculate runoff for the Western Processing study area. The calculations were made using daily precipitation data for 1982 and 1983. The output from the program is a list of runoff estimates for a range of runoff curve numbers. A runoff curve number of 70 was selected for the study area based on the soil type (Group B), land use (residential area with one acre lots), and total impervious area (20%) (Dunne and Leopold, 1978). The curve number 70 converts to a curve number of 85 for normally wet antecedent moisture conditions which is the case for the area around Kent.

The results of the model for the two runoff curve numbers at several storm separation intervals for the year 1982 and 1983 are shown in Table A-1.

Using equation A-1, averaging the runoff for two years and storm separation intervals of one day and two days results in an estimated recharge of about 8 in./yr (20 cm/yr).

TABLE A-1. RUNOFF PROGRAM RESULTS

Storm Separation Interval (days)	Runoff (in./yr) 1982 CN 70	Runoff (in./yr) 1982 CN 85	Runoff (in./yr) 1983 CN 70	Runoff (in./yr) 1983 CN 85
0	0.3	2.5	0.3	2.9
1	6.8	14.8	7.6	17.3
2	7.9	16.9	16.0	25.1
3	11.4	20.5	19.2	28.1

CN = Curve Number

In the final calibrated model a recharge value of 10 in./yr (25 cm/yr) was applied uniformly over the local model region except for two areas on the Western Processing Site. In the area of the pond (Elements 90, 91, 101, 102, 103, 112, 113, and 114) the recharge was increased to 22 in./yr (56 cm/yr), and where the site is asphalted (Elements 128, 129, 130, 143, 144, 145, 146, 152, 153, 154, 163, 164, and 175) no recharge was assumed (0 in./yr).

APPENDIX B

STREAM AND LEAKANCE BOUNDARY CONDITIONS

The boundary conditions in the FE3DGW model were defined using the stream boundary options to describe flux to Mill Creek and the ditch, and the leakance boundary option to describe flux across the perimeter boundaries. This appendix provides a more detailed discussion of the data used in the model to implement these options.

STREAM BOUNDARY OPTION

Surface water bodies are often expressions of the water table and can be treated as such by holding the groundwater elevation at the level of the surface water in a groundwater model. This is not always the case, however, and the stream option in the FE3DGW code allows the potential to fluctuate above or below a stream, and calculates a flux (to or from the stream) based on the potential difference between the elevation of the stream and that of the groundwater. The data required by the model to make this calculation are: the stream surface elevation; the stream bottom elevation, cross-sectional area, thickness, and permeability; and minimum stream depth.

These data were entered into the model for each node along Mill Creek and the drainage ditch. The model calculates the flux to (gaining) or from (losing) each node using Darcy's Law. The data used to implement the stream option in the final calibrated model for Mill Creek and the ditch east of the site are provided in Tables B-1 and B-2, respectively.

The surface water elevation at nodes along Mill Creek and the ditch were interpolated and extrapolated from measurements at five locations along the creek and two along the ditch (Figure 7). The measurements were made on April 10, 1984 by EPA Region X.

TABLE B-1. Stream Boundary Option Data Used to Simulate Flux to Mill Creek.

NODE NUMBER	CREEK ELEVATION	CREEK LENGTH	CREEK WIDTH	CREEK BOTTOM ELEVATION	CREEK BOTTOM THICKNESS	CREEK BOTTOM PERMEABILITY	MIN CREEK DEPTH
2	11.86	246.0	5.0	10.86	0.1	0.142	0.25
12	11.80	369.0	5.0	10.8	0.1	0.142	0.25
22	11.75	279.0	5.0	10.75	0.1	0.142	0.25
33	11.70	246.0	5.0	10.70	0.1	0.142	0.25
34	11.67	246.0	5.0	10.67	0.1	0.142	0.25
35	11.63	246.0	5.0	10.63	0.1	0.142	0.25
47	11.61	148.0	5.0	10.61	0.1	0.142	0.25
58	11.60	98.0	5.0	10.60	0.1	0.142	0.25
75	11.59	140.0	5.0	10.59	0.1	0.142	0.25
92	11.57	131.0	5.0	10.57	0.1	0.142	0.25
122	11.565	100.0	5.0	10.565	0.1	0.142	0.25
134	11.558	100.0	5.0	10.558	0.1	0.142	0.25
150	11.55	74.0	5.0	10.55	0.1	0.142	0.25
159	11.52	50.0	5.0	10.52	0.1	0.142	0.25
177	11.5	82.0	5.0	10.5	0.1	0.142	0.25
186	11.49	98.0	5.0	10.49	0.1	0.142	0.25
204	11.48	115.0	5.0	10.48	0.1	0.142	0.25
214	11.46	130.0	5.0	10.46	0.1	0.142	0.25
230	11.27	165.0	5.0	10.27	0.1	0.142	0.25
239	11.07	215.0	5.0	10.07	0.1	0.142	0.25
251	10.87	246.0	5.0	9.87	0.1	0.142	0.25
263	10.67	295.0	5.0	9.67	0.1	0.142	0.25
275	10.47	295.0	5.0	9.47	0.1	0.142	0.25
287	10.35	340.0	5.0	9.35	0.1	0.142	0.25
288	10.3	277.0	5.0	9.3	0.1	0.142	0.25
289	10.27	295.0	5.0	9.27	0.1	0.142	0.25
290	10.18	328.0	5.0	9.18	0.1	0.142	0.25
301	10.1	360.0	5.0	9.1	0.1	0.142	0.25
309	10.05	215.0	5.0	9.05	0.1	0.142	0.25
286	10.21	180.0	5.0	9.21	0.1	0.142	0.25
285	10.17	230.0	5.0	9.17	0.1	0.142	0.25
272	10.13	262.0	5.0	9.13	0.1	0.142	0.25
271	10.09	328.0	5.0	9.09	0.1	0.142	0.25
270	10.04	328.0	5.0	9.04	0.1	0.142	0.25
282	10.01	360.0	5.0	9.01	0.1	0.142	0.25
293	9.98	190.0	5.0	8.98	0.1	0.142	0.25

TABLE B-2. Stream Boundary Option Data Used to Simulate Flux to the Ditch.

NODE NUMBER	CREEK ELEVATION	CREEK LENGTH	CREEK WIDTH	CREEK BOTTOM			MIN CREEK DEPTH
				ELEVATION	THICKNESS	PERMEABILITY	
54	13.57	66.0	2.0	12.57	0.1	0.142	0.25
65	13.52	125.0	2.0	12.52	0.1	0.142	0.25
82	13.49	108.0	2.0	12.49	0.1	0.142	0.25
99	13.45	82.0	2.0	12.45	0.1	0.142	0.25
111	13.42	57.0	2.0	12.42	0.1	0.142	0.25
115	13.4	57.0	2.0	12.4	0.1	0.142	0.25
129	13.39	66.0	2.0	12.39	0.1	0.142	0.25
141	13.37	70.0	2.0	12.37	0.1	0.142	0.25
157	13.34	66.0	2.0	12.34	0.1	0.142	0.25
166	13.32	57.0	2.0	12.32	0.1	0.142	0.25
184	13.3	57.0	2.0	12.3	0.1	0.142	0.25
193	13.15	73.0	2.0	12.15	0.1	0.142	0.25
209	13.0	82.0	2.0	12.0	0.1	0.142	0.25
219	12.8	125.0	2.0	11.8	0.1	0.142	0.25
233	12.6	73.0	2.0	11.6	0.1	0.142	0.25

LEAKANCE BOUNDARY OPTION

The "leakance boundary condition" option of the FE3DGW code allows flexibility in defining external boundaries of the model region. Rather than specifying a constant flux or held potential at the boundary, the leakance option combines the two and allows the potential and flux to vary depending on the conditions which exist within the study area.

The data required by the model to make this calculation are: the distance from the boundary to a known potential; the potential at that distance; and the cross-sectional area of the boundary. These data are entered into the model for each node along the boundary (both surface nodes and nodes at depth). The model calculates a boundary flux at each node using Darcy's Law, which is in turn used to calculate the potential at the boundary.

A map depicting the regional wells used to calculate the groundwater potential at certain distances from the boundaries is shown in Figure B-1. This map shows the distances to the extended boundary and the gain or loss in potential elevation out to these distances.

The Green River elevations were interpolated from three measurements taken by EPA Region X in April, 1984 :

1. east of benchmark 32 (southwest of site) - 9.8 ft AMSL (3.0 m);
2. east of benchmark 22 (west of site) - 8.8 ft AMSL (2.7 m); and
3. Tukwilla Gauge (north of site) - 7.9 ft AMSL (2.4 m).

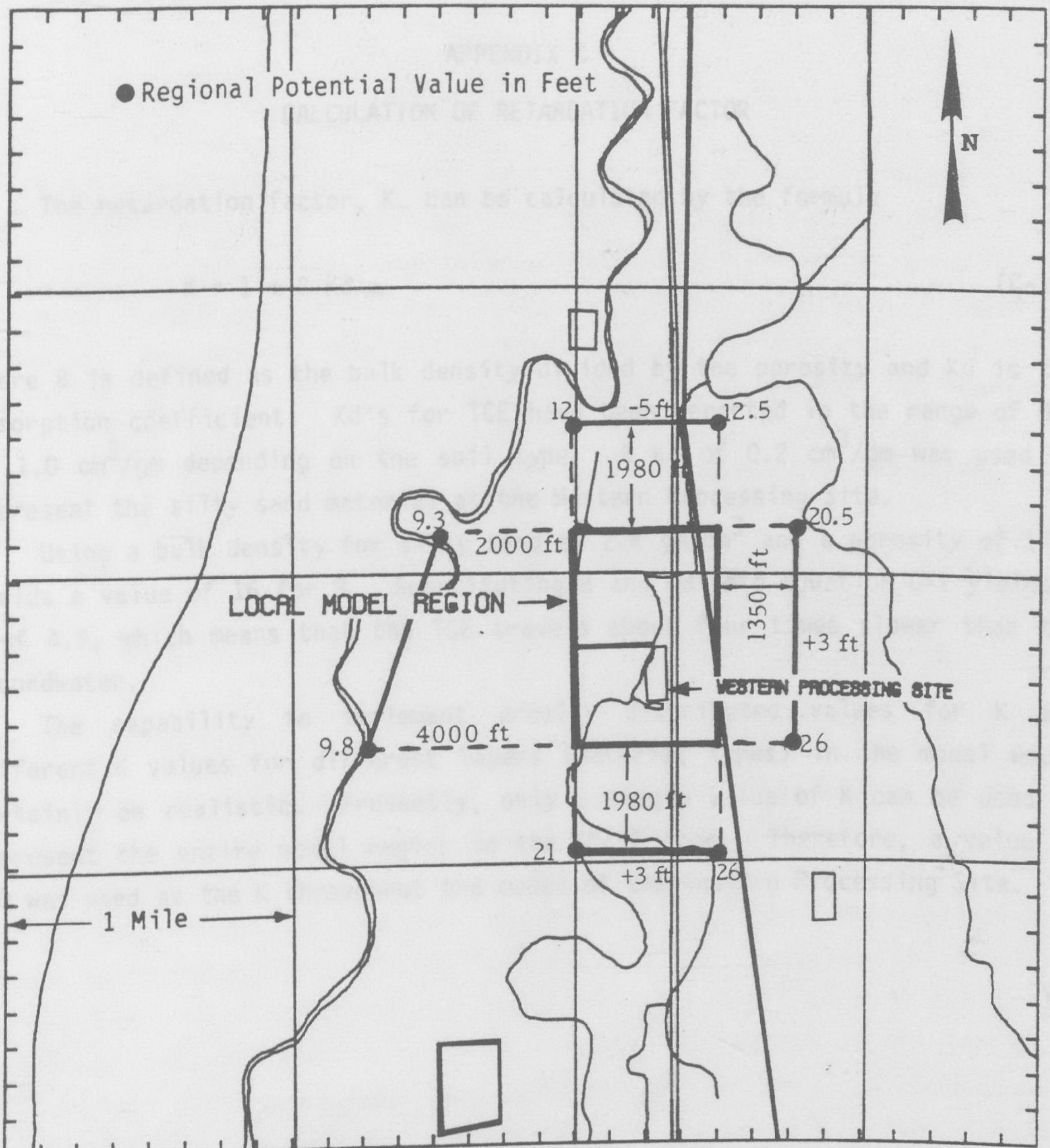

Figure B-1. Locations of Regional Values Used to Determine Boundary Conditions.

APPENDIX C

CALCULATION OF RETARDATION FACTOR

The retardation factor, K, can be calculated by the formula

$$K = 1 + B\ Kd \quad \text{(C-1)}$$

where B is defined as the bulk density divided by the porosity and Kd is the adsorption coefficient. Kd's for TCE have been reported in the range of 0.1 to 1.0 cm^3/gm depending on the soil type. A Kd of 0.2 cm^3/gm was used to represent the silty sand material at the Western Processing Site.

Using a bulk density for silty sand of 2.4 gm/cm^3 and a porosity of 15%, yields a value of 16 for B. Substituting B and Kd into equation C-1 yields a K of 4.2, which means that the TCE travels about four times slower than the groundwater.

The capability to implement areally distributed values for K and different K values for different layers (material types) in the model would certainly be realistic. Presently, only a single value of K can be used to represent the entire model region in the CFEST code. Therefore, a value of 4.0 was used as the K throughout the model of the Western Processing Site.

APPENDIX D
MODEL CALIBRATION

About 35 computer simulation runs were made in the groundwater flow model calibration process. During this process the difference between the model-predicted and measured hydraulic potentials were minimized by adjusting the model parameters which were least well known. Because a range of parameters was tested, the calibration process can be considered as a sensitivity analysis. If certain input parameters are changed too severely, the difference between the model-predicted and measured potentials increases dramatically. This process provides a range of reasonable values for the model input parameters.

A few of the model calibration runs are discussed in this appendix to demonstrate the sensitivity of the model to the primary calibration parameters of horizontal and vertical hydraulic conductivity and stream flux.

HYDRAULIC CONDUCTIVITY

A range of horizontal hydraulic conductivities (Kh) between 30 ft/day (9 m/day) and 0.3 ft/day (0.1 m/day) were tested in the model during the calibration process. When the Kh was large, the resulting potential surface did not depict the groundwater mound that has been observed on-site (Figure D-1). Conversely, when the Kh was set at the low value, the potential surface increased significantly as shown in Figure D-2. A Kh of 2.8 ft/day (0.9 m/day) over the model area and 0.3 ft/day (0.1 m/day) in the top 10 ft (3 m) on site produced the best match with observed potentials (Figure 2).

Vertical hydraulic conductivities (Kv) in the range 1/10 to 1/100 the value of the horizontal hydraulic conductivity were tested in the model (Kv/Kh = 1/10 or 1/100). As was the case for changes in Kh, if the Kv is too large it allows most of the water to infiltrate and the resulting potential surface does not depict the groundwater mounding on site. Similarly, if the

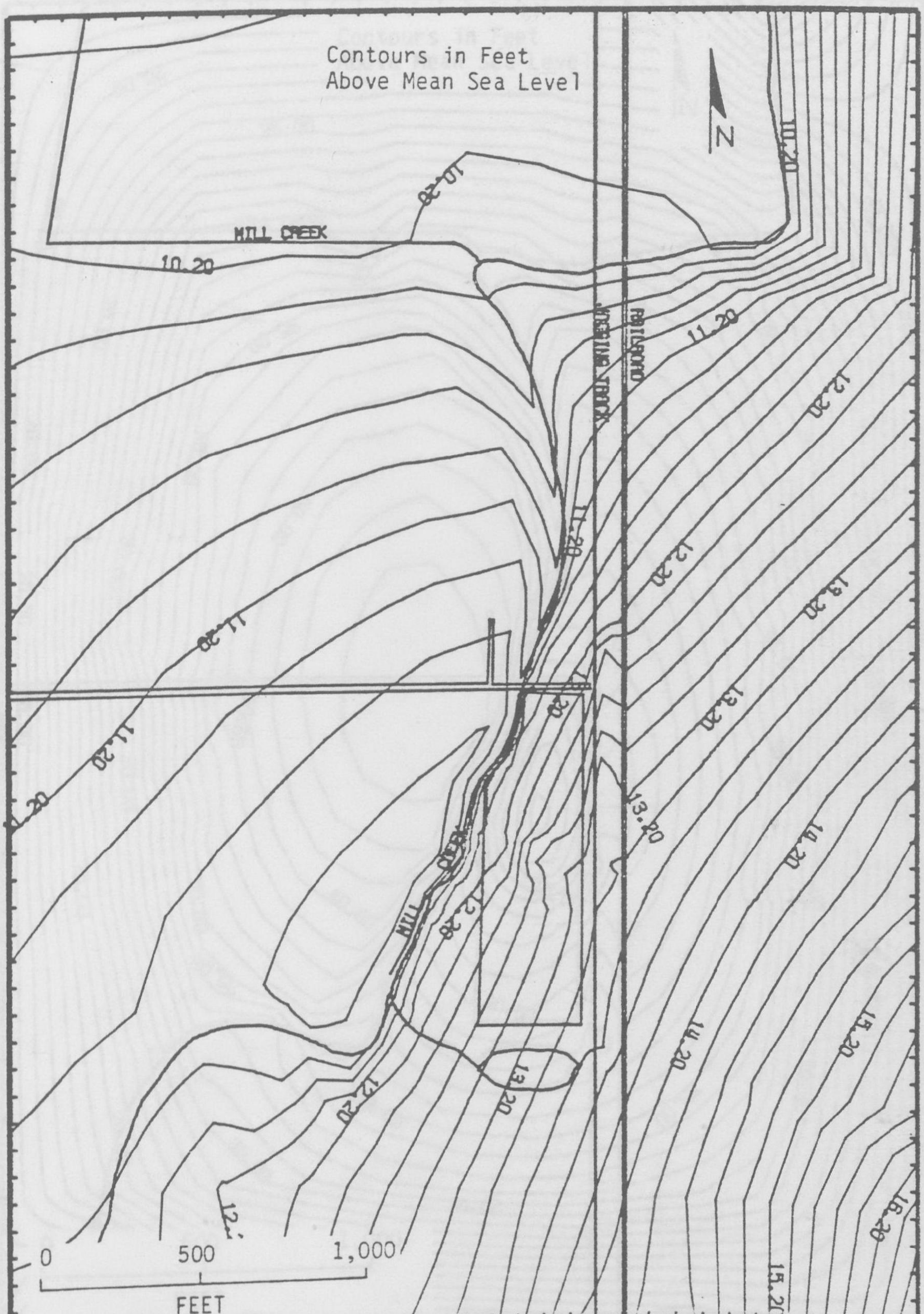

Figure D-1. Model-Predicted Water Table Surface for Kh = 28.4 ft/day.

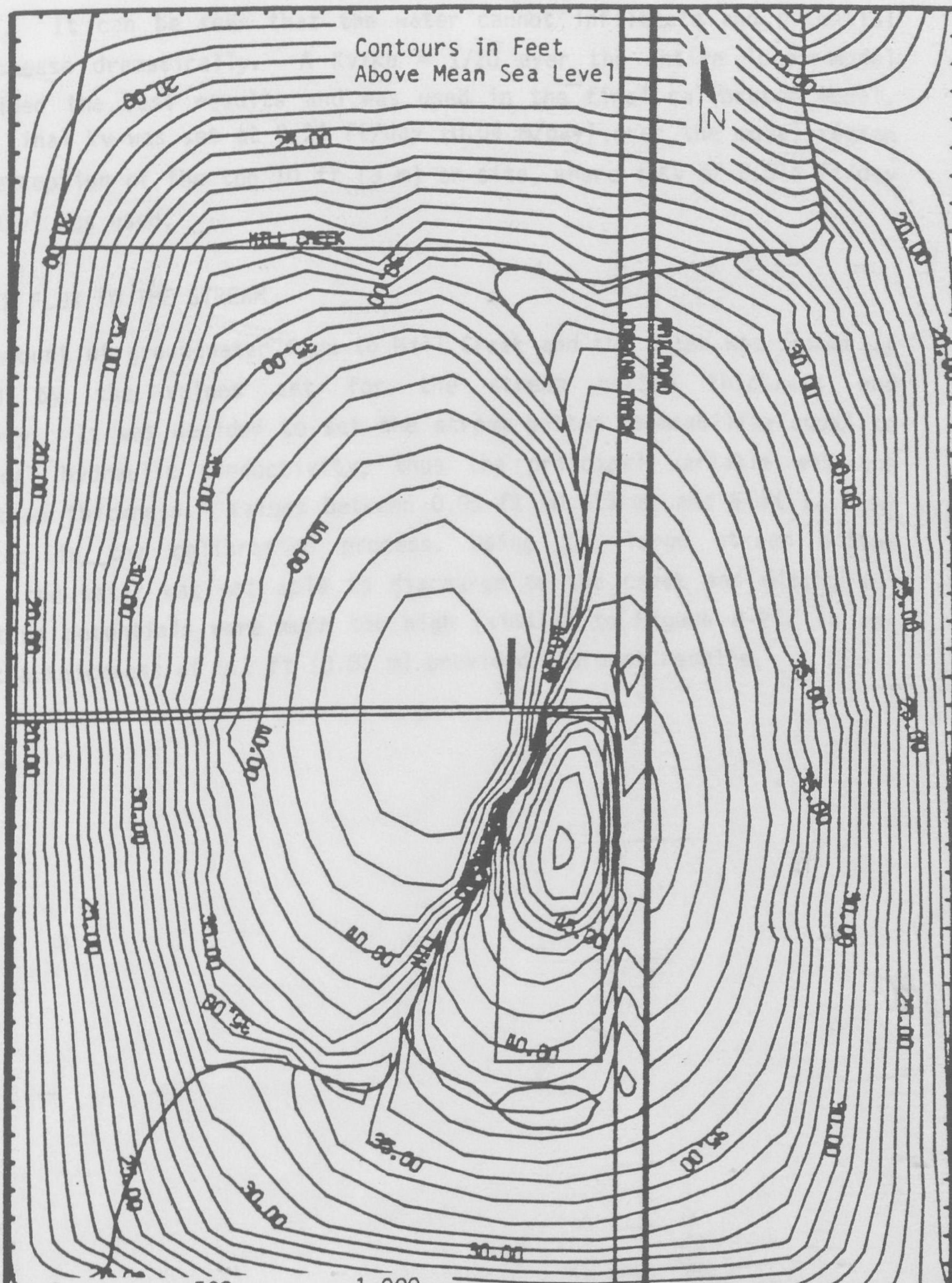

Figure D-2. Model-Predicted Water Table Surface for Kh = 0.3 ft/day.

Kv is too low, the water cannot infiltrate and the potential values increase significantly. A calibration run where the Kv/Kh = 1/100 is shown in Figure D-3. It can be seen that the water cannot infiltrate and potential values increase dramatically. A Kv/Kh = 1/20 over the entire local model area provided the best results and was used in the final calibrated model. Thus, the final Kv was set at 0.14 ft/day (0.04 m/day) over the model region with the exception of the top 10 ft (3 m) on site, where a Kv of 0.014 ft/day (0.004 m/day) was used.

GROUNDWATER FLUX TO THE STREAM

The amount of groundwater flux to Mill Creek and the ditch was primarily controlled by the values set for the stream bottom thickness and permeability. It was decided to set the stream bottom permeability equal to the vertical hydraulic conductivity, thus the principal variable was the stream bottom thickness. Values between 0.05 ft (0.015 m) and 5 ft (1.5 m) were tested in the calibration process. Using the large stream bottom thickness, the water was not able to discharge to the creek and ditch, and the resulting potentials were much too high (similar to Figure D-2). It was found that a thickness of 0.1 ft (0.03 m) provided the best results.

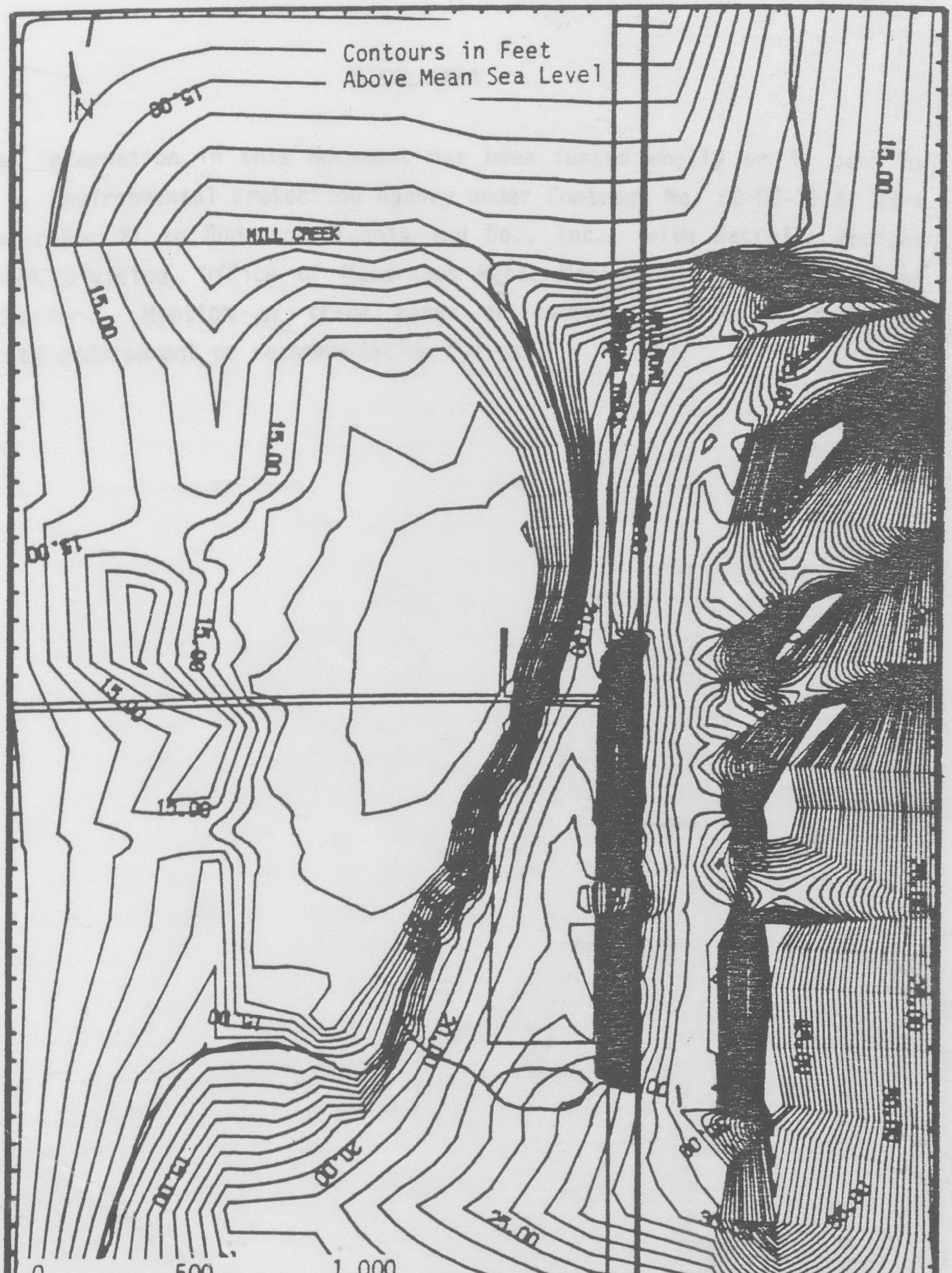

Figure D-3. Model-Predicted Water Table Surface for Kv/Kh = 1/100

DISCLAIMER

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ABSTRACT

Western Processing Hazardous Waste Site consists of 13-acres near Kent, Washington, which operated as an industrial waste recycling facility from about 1960 through 1982. During 1982, the U.S. Environmental Protection Agency (EPA) conducted surface water sampling around the site and found 26 priority pollutants; all of which were subsequently found on site. As a result of these findings and subsequent studies, the EPA initiated several studies to characterize the site and evaluate remedial action alternatives.

One of the efforts initiated by the EPA was to develop groundwater flow and contaminant transport models of the site to be used in evaluating proposed remedial actions. The development and calibration of these models and their use in evaluating remedial actions is discussed in this report.

A conceptual model of the study area was formulated based on the available hydrogeologic and contaminant data. The conceptual model formed the framework for developing the groundwater flow and contaminant transport models of the area around the Western Processing Site.

Once calibrated, the model was used to evaluate the effectiveness of six proposed remedial actions: 1) no-action, 2) source removal, 3) cap, 4) source removal combined with a cap, 5) upgradient slurry wall combined with a cap, and 6) pump and treat. Of these potential actions, pump and treat produced the most favorable results in the simulation. Considering only passive remedial actions the simulated source removal case produced the best results.

The results of the remedial action simulations are preliminary in nature because the model was run only once for each scenario; optimization runs and sensitivity analyses were not performed. It is recommended that as more data become available, the models be further calibrated and validated and that a more thorough modeling analysis of the remedial actions be performed.

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