REMEDIAL ACTION MODELING ASSESSMENT
WESTERN PROCESSING SITE, KENT, WASHINGTON

Draft

by

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DISCLAIMER

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ABSTRACT

The 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 efforts, the EPA initiated a series of studies to characterize the site and evaluate remedial action alternatives.

One of the efforts initiated by the EPA was to develop a groundwater flow and contaminant transport model of the site to be used in evaluating proposed remedial actions. The development and calibration of this model and its 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 model of the area around the Western Processing Site.

Once calibrated a limited sensitivity analysis was performed to determine the sensitivity of the model results to changes in hydraulic conductivity, porosity, recharge, dispersivity, and retardation factor. The model was used to evaluate the effectiveness of remedial actions proposed by CH2M HILL and the Potentially Responsible Parties, as well as minor modifications. The remedial actions considered include: 1) no-action; 2) source removal; 3) source removal and pump and treat; 4) capping and pump and treat; 5) source removal and a slurry wall; and 6) source removal, slurry wall, and pump and treat. Pumping rates of both 100 gpm and 200 gpm were simulated in the model.

Of the remedial actions simulated, source removal combined with pump and treat was found to provide the greatest reduction in mass of trichloroethylene (TCE) from the groundwater flow system. Simulations showed that all TCE was removed from the groundwater flow system in 15 and 5 years at the 100 gpm and 200 gpm pumping rates, respectively. The slurry wall around the site prevented the removal of TCE that was off site, but was effective in reducing the lateral flow of clean water to wells during pumping and containing contamination after pumping ceases.

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SECTION 1

INTRODUCTION

The goal of this project was to evaluate remedial action alternatives for the Western Processing Hazardous Waste Site in Kent, Washington, using a calibrated groundwater flow and contaminant transport model. The specific tasks of the study included:

- review available data and identify deficiencies;
- develop a groundwater flow and contaminant transport model of the study area;
- calibrate the flow and transport model with existing data;
- perform a limited sensitivity analysis with the final calibrated model; and
- evaluate remedial action alternatives for the site with the calibrated model.

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 model of the site.

The Finite Element Three-Dimensional Groundwater (FE3DGW) code (Gupta et al., 1979) was initially used to model the groundwater flow within an area at and 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 in the code. Once the flow model was calibrated, these data were input to the three-dimensional Coupled Fluid, Energy, and Solute Transport (CFEST) code (Gupta et al., 1982) to simulate the groundwater flow and 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.

Once developed, the flow and transport portions of the model were calibrated to observed 1982 through 1984 potentiometric and contamination data provided by EPA Region X. In this phase of the project, the transport modeling was based strictly on observed concentrations of trichloroethylene (TCE) in the groundwater, surface water, and soil at the site. A limited sensitivity analysis was performed with the final calibrated (base case) model in order to test the sensitivity of the model results to variations in the basic model input parameters.

The final calibrated flow and transport model was used to predict the effectiveness of remedial action alternatives proposed for the Western Processing Site by CH2M HILL and the Potentially Responsible Parties (PRPs). The CH2M HILL proposed actions were: 1) source removal combined with pump and treat; and 2) cap combined with pump and treat. The PRPs proposed action (Landau Associates and Dames and Moore, 1984) consisted of a combination of source removal, a slurry wall around the site, and pump and treat. In addition to the basic remedial action runs, a no-action run (extending the base case run into the future) was performed to provide a benchmark against which remedial action results could be compared. Also, a few minor variations (e.g., using different combinations of actions and variable pumping rates) to the basic remedial action runs were simulated in order to better understand the model results.

In all cases, the flow portion of the model was used to predict changes in the groundwater potential (i.e., drawdown) and volumes of water removed. The contaminant transport portion of the model was used to predict the mass of TCE removed from the system and average concentrations up to 50 years into the future.

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 TCE concentrations, as well as accurately predicting the groundwater gain of Mill Creek over the model region, and the concentration of TCE in the creek. The model was also able to closely match the estimated total mass of TCE in the groundwater flow system based on monitoring data for the period 1982 through 1984.

A limited sensitivity analysis was performed to determine the sensitivity of the model results to changes in hydraulic conductivity, porosity, recharge, dispersivity, and retardation factor. The analysis showed that all parameters tested have some impact on the results of the final calibrated model, and no parameter can be changed without altering the current calibration.

The final calibrated model was used to evaluate the effectiveness of remedial actions proposed by CH2M HILL and the PRPs. All model runs have simulated the transport of TCE. Other contaminants on site will behave differently because they have different sorption properties, are present in different quantities at the site, and/or have different source locations). It is important to keep this in mind when extrapolating the model results for TCE to a more comprehensive remedial action for all contaminants on site.

A summary of the results for all remedial action simulation runs is shown in Table 1. A comparison of the total mass of TCE remaining in the groundwater flow system for the CH2M HILL and PRPs remedial action cases are shown in Figure 1a and 1b, respectively. The CH2M HILL PRPs base case and no-action cases show essentially the same results. The only difference is that the slurry wall elements in the PRPs case reduced the size of the

TABLE 1. SUMMARY OF THE MODEL RESULTS FOR THE CH2M HILL AND PRPS REMEDIAL ACTION SIMULATIONS.

Cases	TCE in System in 1988 (lb)	TCE in System in 1993 (lb)	TCE Discharging to Mill Creek 1983 - 1988 (lb)	TCE Discharging to Mill Creek 1988 - 1993 (lb)	% TCE Discharging to Mill Creek and Ditch	% TCE Withdrawn by Pumping Wells	Years to Remove all TCE	Years to Remove 90% of the TCE	Average Drawdown Over Site (ft)
CH2M HILL Cases									
No-Action	13,075	9,611	4,822	3,597	100	N/A	>50	30	N/A
Source Removal	12,141	8,587	4,781	3,447	100	N/A	>50	30	N/A
Source Removal, Pump and Treat (100 gpm)	1,511	593	1,824	246	13	87	15	5	4.0
Source Removal, Pump and Treat (200 gpm)	0	0	529	0	3	97	5	<5	8.5
Cap, Pump and Treat (100 gpm)	1,307	584	1,767	213	9	91	15	5	4.5
Cap, Pump and Treat (200 gpm)	0	0	500	0	3	97	5	<5	9.0
PRPs Cases									
No-Action	12,389	9,136	4,480	3,392	100	N/A	>50	30	N/A
Source Removal	12,388	9,875	3,536	2,438	100	N/A	>50	40	N/A
Source Removal, Slurry Wall, Pump and Treat (100 gpm)	2,577	1,069	2,349	1,463	18	82	15	10	6.0
Source Removal, Slurry Wall, Pump and Treat (200 gpm)	0	0	467	0	3	97	5	<5	12.0
Source Removal, Pump and Treat (100 gpm)	1,276	845	1,575	418	11	89	20	5	4.0
Source Removal, Pump and Treat (200 gpm)	0	0	467	0	3	97	5	5	8.5

N/A = Not Applicable

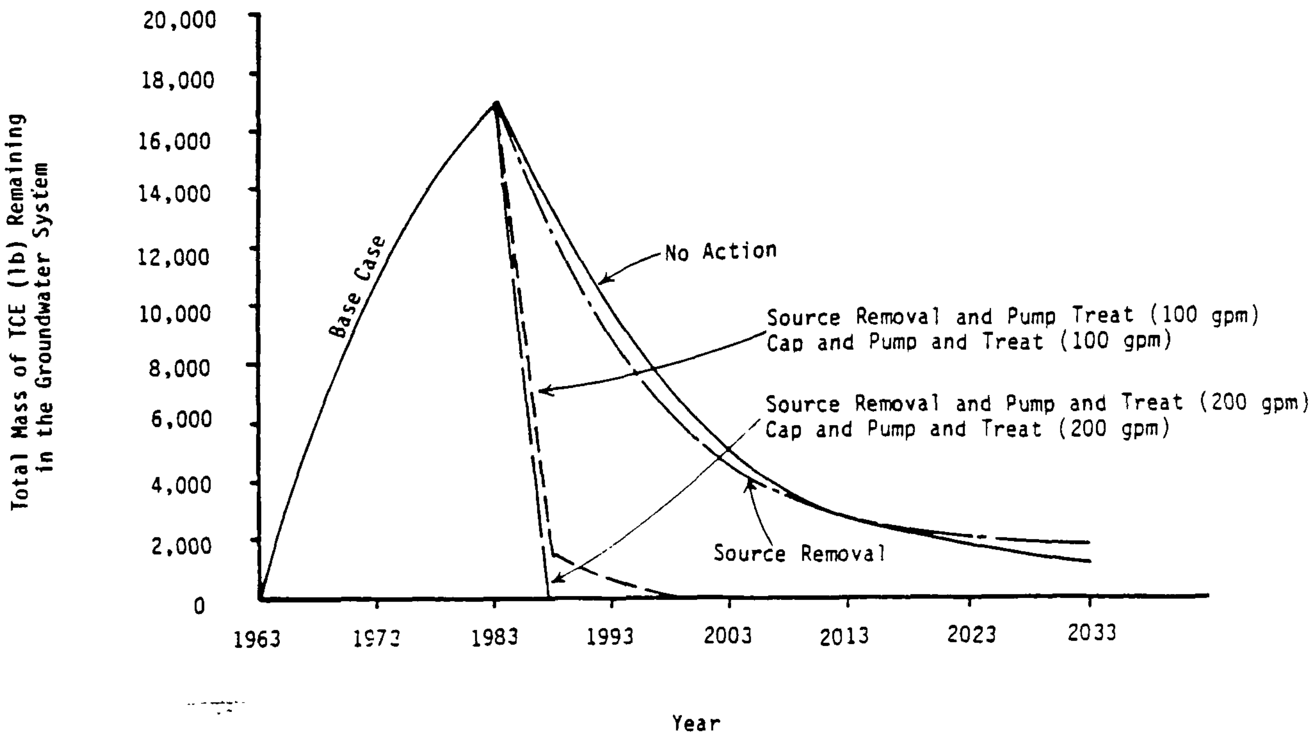


Figure 1a. Comparison of the Total Mass of TCE Remaining in the Groundwater Flow System for the CH2M Hill Remedial Action Cases

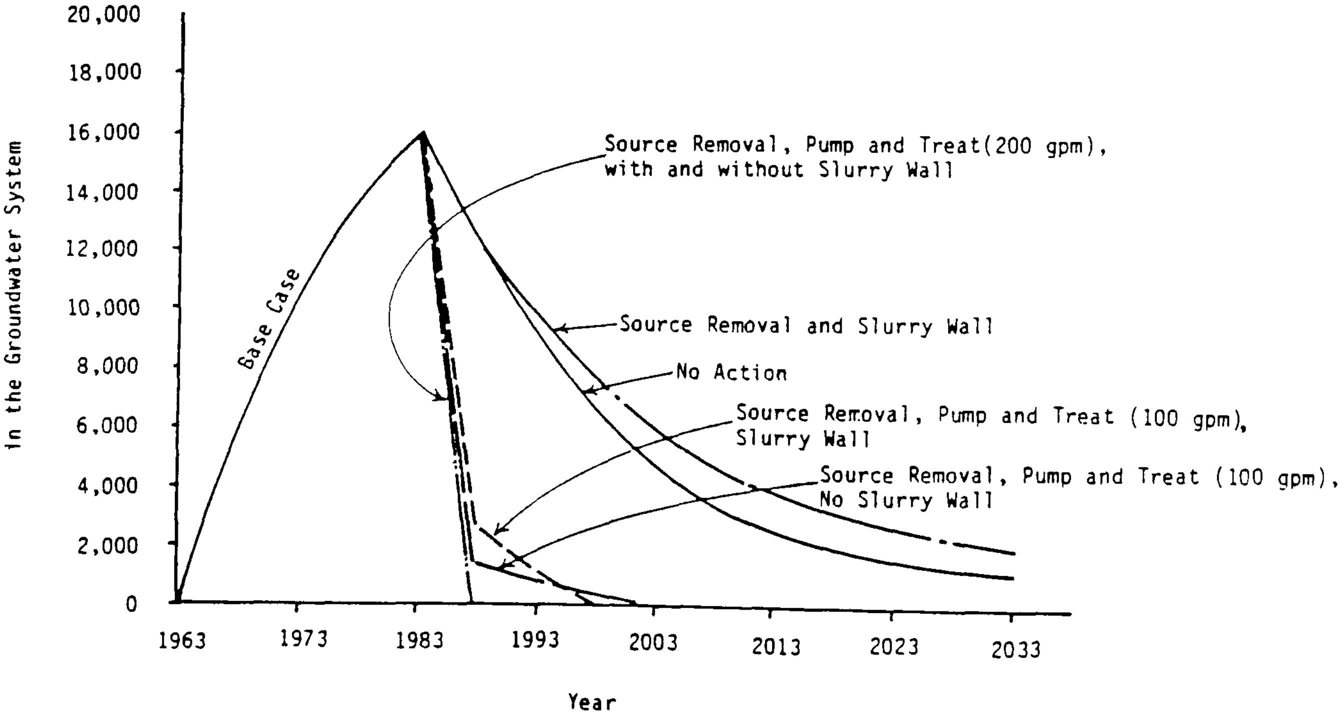


Figure 1b. Comparison of the Total Mass of TCE Remaining in the Groundwater Flow System for the PRPs Remedial Action Cases

Reaction Pond III and Well 21 source area which in turn, slightly reduced the mass loading to the system.

The results for the pump and treat where the wells were pumping 200 gpm (758 l/min) showed that all of the TCE would be removed from the system in the first 5 years. All cases where the wells were pumping 100 gpm (379 l/min) showed that 85% to 90% of the TCE is removed in the first 5 years and the remainder is removed within the next 10 to 15 years. The slurry wall in the PRPs cases prevented the pumping wells from removing TCE that had moved off site, and therefore, the simulations with the wall were less effective at removing the TCE.

There do exist some small differences in the results for the various model simulations. But, for the most part, all remedial actions were about equally effective in cleaning up the TCE in a 5 to 15 year time period.

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 2). 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.

During the fall and winter of 1984, the site was partially excavated to remove surface structures, waste piles, and some of the contaminated soil. The modeling discussed in this document uses the pre-excavation ground-surface elevation (averaging 25 ft above mean sea level) as a reference point.

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 2 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 8 in./yr (20 cm/yr) was obtained. A detailed description of recharge calculations is contained in Appendix B.

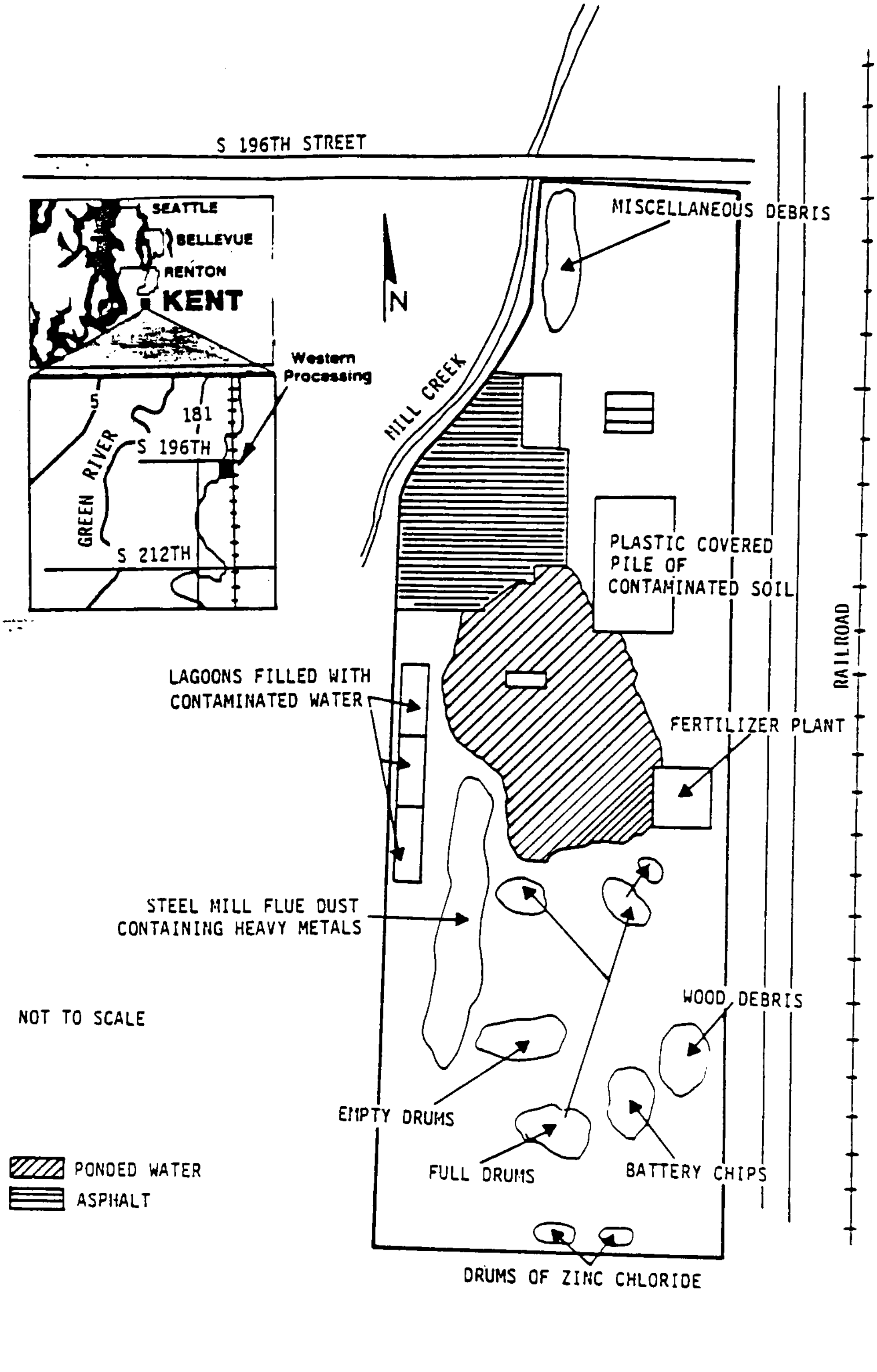


Figure 2. Western Processing Site Before 1984 Excavation

TABLE 2. 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)

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. 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 top 8 ft (2.4 m) underlying the Western Processing Site consists primarily of unsaturated artificial fill material. Below the fill, the site is underlain by a mixture of sand, silt, clay, and peat to a depth of approximately 40 ft (12 m) (Unit 1). Intermittent clay lenses are present in this layer (Hart-Crowser, 1984). From 40 to 150 ft (12 to 46 m) below the surface (Unit 2) the material consists predominantly of fine to medium sand with occasional layers of silty and/or gravelly sand (Hart-Crowser, 1984). Underlying Unit 2 is a thick (greater than 218 ft) layer of silt which forms an aquitard (CH2M HILL, 1984).

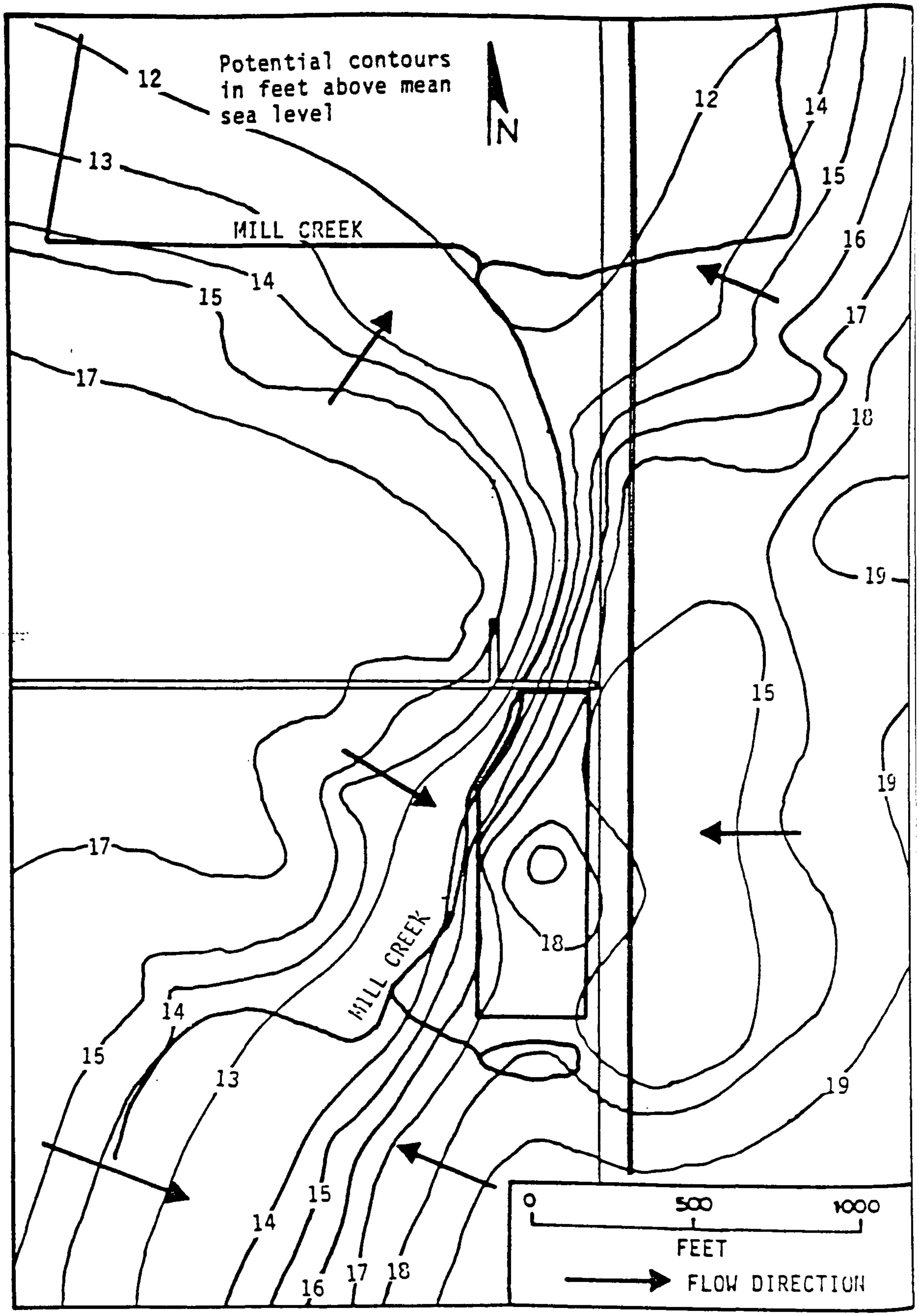


Figure 3. Smoothed Kriged Potential Surface for April, 1984

site. As a result of this action, disposal at the site ceased in 1982. In 1982 and 1983, the EPA installed a series of monitor 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.

In 1984, the EPA did more extensive excavation, removing all of the structures and materials (drums, waste piles, buildings, etc.) on site and removing some of the contaminated soil. Waste disposal records for the site are sketchy; however, a review of the records that are available indicates 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.

There is no evidence that trans-1,2-dichloroethylene (DCE) had ever been received at the site, however, DCE has been found on site in both soil and groundwater samples. In some cases the level of DCE approaches or exceeds the level of TCE.

As a general trend, it has been found that the occurrence of the dichlorinated species increases downgradient from source areas. These findings led to the conclusion that degradation of TCE is the likely source of DCE. The most plausible mechanism for such a transformation is biodegradation (Wood et al., 1981).

As a result of these determinations, the contaminant transport model calibration assumed that this TCE to DCE transformation process occurs. Because this transformation cannot be simulated in the model, the sum of TCE and DCE concentrations was used to calibrate the model.

The high TCE concentrations measured in the soil and/or groundwater in Wells 11, 15, 17, 20, 21, and 27 (Figure 4) indicates the existance of three probable TCE source areas: 1) Reaction Pond I; 2) Reaction Pond III; and 3) around Well 21. A summary of the measured TCE and DCE concentrations in the soil and groundwater at the three suspected source locations is shown in Table 4. The sum of the TCE and DCE concentrations in the groundwater was used for model calibration.

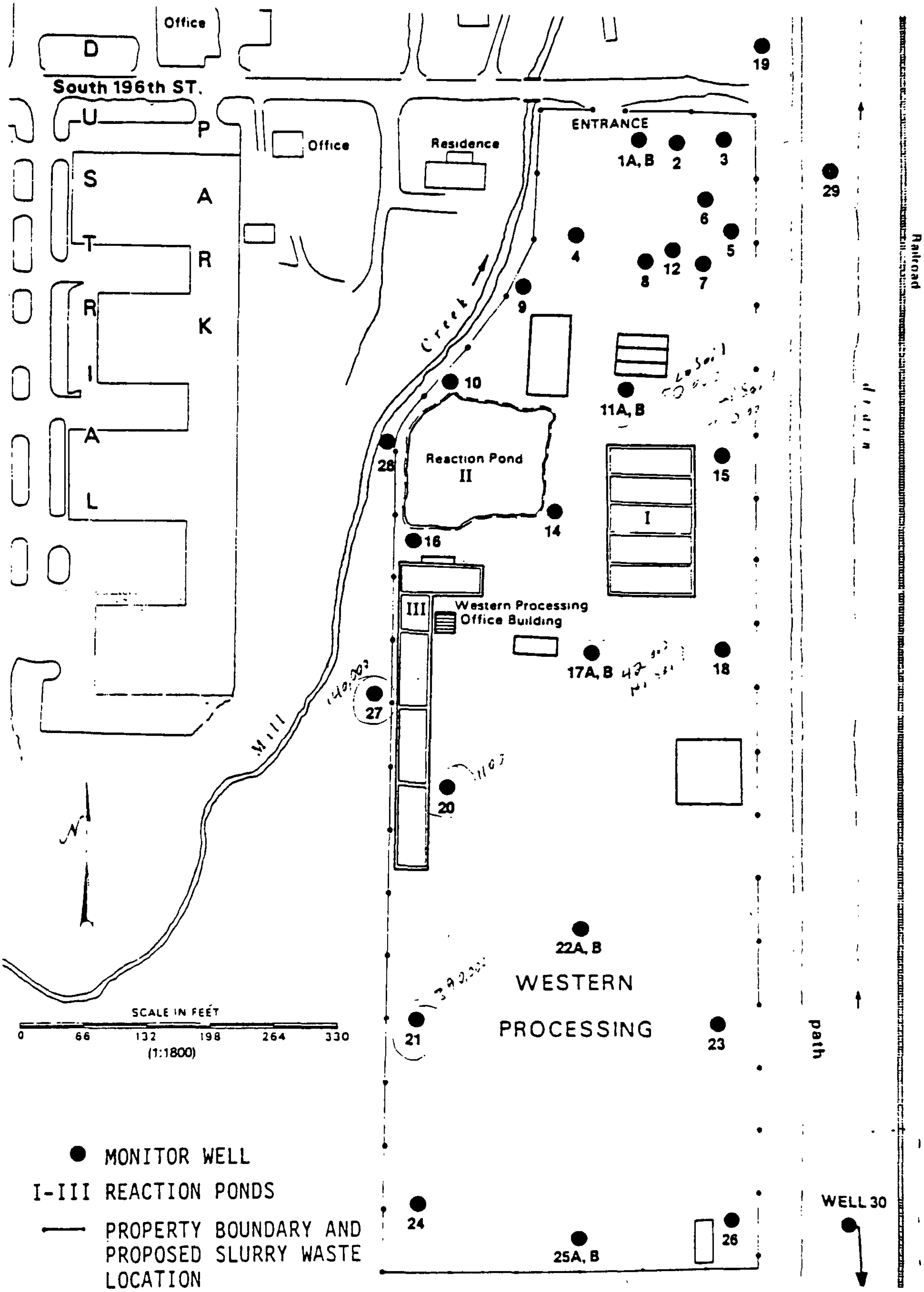


Figure 4. Western Processing Well and Reaction Pond Locations

TABLE 4. SUMMARY OF SOIL AND GROUNDWATER CONCENTRATIONS OF TCE AND DCE (EPA, 1982) AT THE THREE SUSPECTED SOURCE AREAS

Source	Associated Well Number	Concentration TCE (ppb)		Concentration DCE (ppb)		Total TCE and DCE in Groundwater
		Soil	Groundwater	Soil	Groundwater	
Reaction Pond I	11	312	80,000	0	0	80,000
	15	580,000	210,000	0	0	210,000*
	17	558,000	42,000	0	0	42,000
Reaction Pond III	20	676	1,100	0	0	1,000
	27	NS	140,000	NS	0	140,000*
Around Well 21	21	1,520	170,000	24	390,000	560,000*

NS = No soil samples taken.
*Concentration matched in the model calibration process.
Soil samples may have been taken from either the saturated or unsaturated zone and were not necessarily in contact with the groundwater.

The maximum observed TCE concentration in groundwater is 210,000 ppb, while the maximum observed soil concentration is 558,000 ppb. The EPA priority pollutant human health criteria for TCE in water is 27 ppb at 10^{-5} cancer risk (EPA, 1980).

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: 1) variations in permeability with depth; 2) the vertical flow within the study area; 3) localized discharge to Mill Creek and the drainage ditch; and 4) slurry wall and pumping depths in the proposed remedial actions.

The numerical codes selected to model the Western Processing Site are the FE3DGW flow code and the CFEST transport code. The FE3DGW code simulates groundwater flow while its companion code, CFEST, simulates contaminant transport coupled with groundwater flow. 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 (Gupta et al., 1979 and 1982).

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 5).

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 6.

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 with intermittent clay lenses (Unit 1 as defined in the previous section). The intermittent clay lenses were simulated by reducing the ratio of vertical to horizontal permeability. A coarser sand material (Unit 2 as defined in the previous section) was simulated between 30 and 100 ft (9 and 30 m) below the water table.

Although the region was simulated with two geologic units, the vertical dimension in the model was simulated as four layers. Layers 1 and 2 composed Unit 1, while Layers 3 and 4 composed Unit 2. The layer thicknesses from top to bottom were 13 ft (4 m), 17 ft (5 m), 10 ft (3 m), and 60 ft (18 m). This subdivision of geologic units allowed for more vertical resolution in the model, as well as allowing an accurate representation of pumping depth, source removal depth, and slurry wall depth in the remedial action simulations.

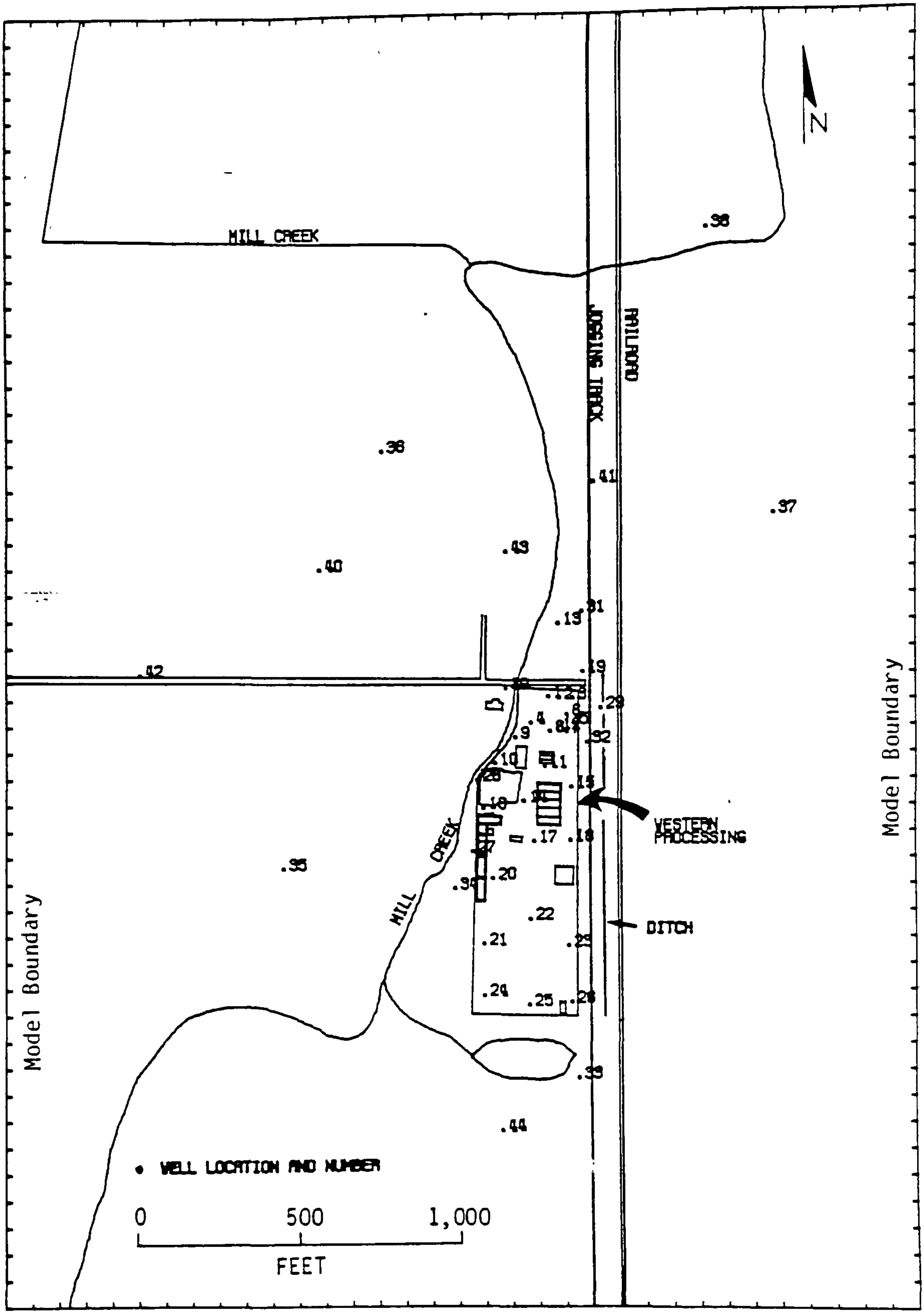


Figure 5. Western Processing Model Area

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 assumed to be hydraulically connected to the groundwater system.

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 at each node along Mill Creek and the ditch, were interpolated or extrapolated from surveyed values obtained in April, 1984 (Figure 7). A more detailed description of the boundary conditions is provided in Appendix C.

Hydraulic Conductivity

Initially, horizontal (Kh) and vertical (Kv) hydraulic conductivities were assigned to the two material types discussed above based on data in the Hart-Crowser report (1984). 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 (Units 1 and 2) are shown in Table 5. The values were uniform throughout each layer. For both material types, the final calibrated values were within the range of values reported by Hart-Crowser (1984).

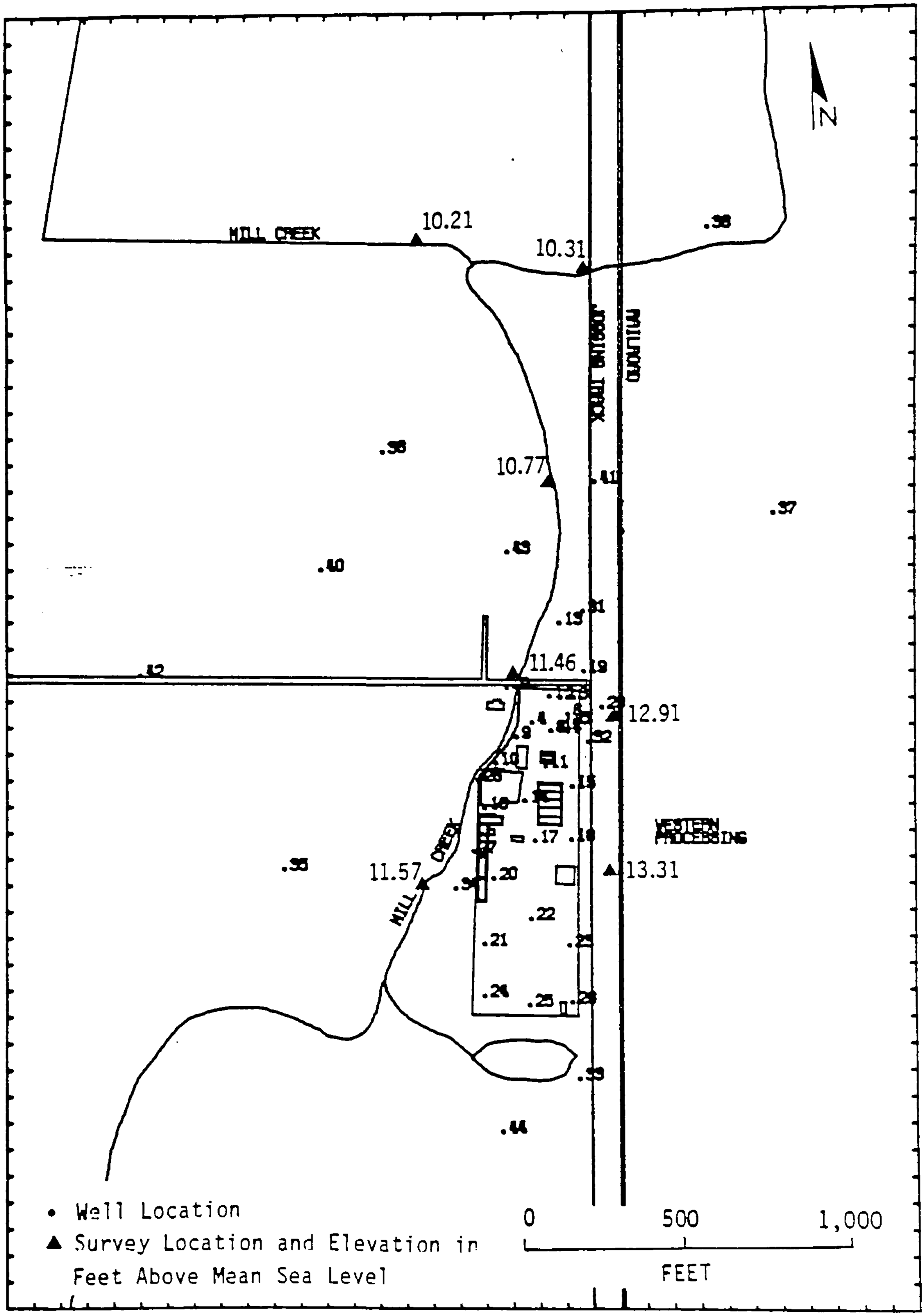


Figure 7. Location of Surveyed Values for Mill Creek and Drainage Ditch

TABLE 5. PARAMETERS USED IN THE FINAL CALIBRATED GROUNDWATER FLOW AND CONTAMINANT TRANSPORT MODEL

	Model Layer			
	1	2	3	4
Structure				
Top (ft AMSL)	15	2	-15	-25
Bottom (ft AMSL)	2	-15	-25	-85
Thickness (ft)	13	17	10	60
Horizontal Hydraulic Conductivity (ft/day)	3.5	3.5	50	50
Vertical Hydraulic Conductivity (ft/day)	0.175	0.175	5	5
Kv/Kh	0.05	0.05	0.1	0.1
Effective Porosity	0.15	0.15	0.15	0.15
Longitudinal Dispersivity (ft)	25	25	25	25
Transverse Dispersivity (ft)	5	5	5	5
Retardation Factor	4	4	4	4
Lithology	silty sand	silty sand	sand	sand

Surface Recharge = 8.0 in./yr

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 showed that, the potentials do not change enough to significantly alter the flow field or flow velocities. Therefore, the steady state assumption is considered to be acceptable for the modeling effort.

A contour surface of the April, 1984 potential data was used to represent the initial potential conditions (Figure 3). This surface was prepared by kriging potential data from 36 wells on and around the site, and 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 8 in./yr (20 cm/yr). The only exception was in the asphalted (capped) area on the site (Figure 2) where recharge was set at 0 in./yr. A detailed description of the recharge calculations is contained in Appendix B.

Porosity

Measured values of porosity are not available for the Western Processing Site. As a reasonable estimate, an effective porosity of 15% was used in all layers of the model.

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 showed that TCE was accepted 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.

As discussed earlier, the DCE observed on site is believed to be a degradation product of the TCE. Since the model is not capable of simulating this degradation process, the initial mass (concentration) of TCE was assumed to be the total mass (concentration) of TCE plus DCE. The total concentration of TCE plus DCE at each of the three suspected source areas is shown in Table 4. These totals are the concentrations that were matched in the model calibration process. From this point on, the total of TCE plus DCE will be referred to simply as TCE.

Source Location

A review of the sampling results for TCE in the on-site wells (EPA, 1983) reveals three probable source areas: 1) Reaction Pond I; 2) Reaction Pond III; and 3) around Well 21. The area of the finite elements used to simulate Reaction Ponds I and III was set to represent the actual areas of these ponds. Reaction Pond I was represented in the model by elements with an area of 7,800 ft^2 (750 m^2). Reaction Pond III was represented in the model by elements with an area of 7,050 ft^2 (655 m^2).

For an unknown number of years during the operation of the site, TCE was mixed with fly ash in the area around Well 21. High concentrations of TCE in both the soil and groundwater at the location of Well 21 indicate a probable source. The area of this source is unknown, therefore, it was determined in the model calibration process by the area which resulted in the desired concentration and mass loading of TCE. In the final calibrated model the source around Well 21 was represented by an element with an area of 1,600 ft^2 (149 m^2).

Source Area Concentrations

Leaching of TCE into the groundwater, rather than direct infiltration, was the primary mechanism for introducing TCE to the model. Therefore, the initial TCE concentration was defined at the elements representing the three source areas, and the loading rate at each site was calculated as the infiltration rate times the surface area of the source times the initial TCE concentration at the source. The initial TCE concentrations at the three sources were defined as follows: Reaction Pond I -- 6.0×10^5 ppb, Reaction Pond III -- 1.9×10^6 ppb, and around Well 21 --1.15×10^7 ppb. The infiltration rate was constant over the entire model region at 8 in./yr (20 cm/yr). Using the areas for each source given above, the loading rates in the model at Reaction Ponds I and III, and around Well 21 were 195 lb/yr (88 Kg/yr), 559 lb/yr (254 Kg/yr), and 769 lb/yr (349 Kg/yr), respectively, over the 20-year active disposal life of the site. The total model-predicted mass of TCE disposal at the site was 1,523 lb/yr (689 Kg/yr) or 30,460 lb (13,781 Kg) over the 20-year disposal period.

Source Duration/Leach Rate

The sources were assumed to be actively leaching TCE into the groundwater for 20 years, from 1963 through 1983. The rate of leaching was constant over the 20 years at the rates given above.

The mass of TCE currently in the unsaturated zone at the three source areas was estimated to determine how long leaching into the saturated flow system would continue (see Appendix A). This information was used to determine how long to keep the sources active in the model. The results of these calculations indicate that virtually all the mass of TCE in the unsaturated zone beneath Reation Pond III and around Well 21 has already leached into the saturated zone. Therefore, these two sources were turned off in the model in 1983. The calculations show that Reaction Pond I would continue to leach TCE into the groundwater for about 20 years, and that the rate decreases exponentially. Based on the calculations, the model input concentration at Reaction Pond I was set at full strengh (6×10^5 ppb) for the first five years into the future (1984 - 1988), and then it was reduced by 75% at each of the next three time steps (1989 - 1993 = 50,000 ppb, 1994 -

1998 = 37,500 ppb, and 1999 - 2003 = 9,400 ppb). After the year 2003, all sources of TCE were turned off in the model.

Sorption/Retardation

The CFEST model uses a single retardation factor for the entire groundwater flow system (all layers), which was determined in the model calibration process. The retardation factor used in the final calibrated model was 4.0.

The retardation factor can be calculated from the bulk density, actual and effective porosity, and the distribution coefficient (Kd) for the material through which flow occurs. A discussion of these parameters and how they relate to a retardation factor of 4.0 is contained in Appendix D.

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 3) and the conceptual model of the flow regime within the study area (i.e., localized flow to Mill Creek and the ditch, and regional flow to the northwest). Potential surfaces for the model-predicted top of Layers 2, 3, 4, and the bottom of Layer 4 are shown in Figures 9, 10, 11, and 12, respectively. The model-predicted groundwater flux to Mill Creek along the reach within the study area is 0.45 cfs (1,101 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.

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

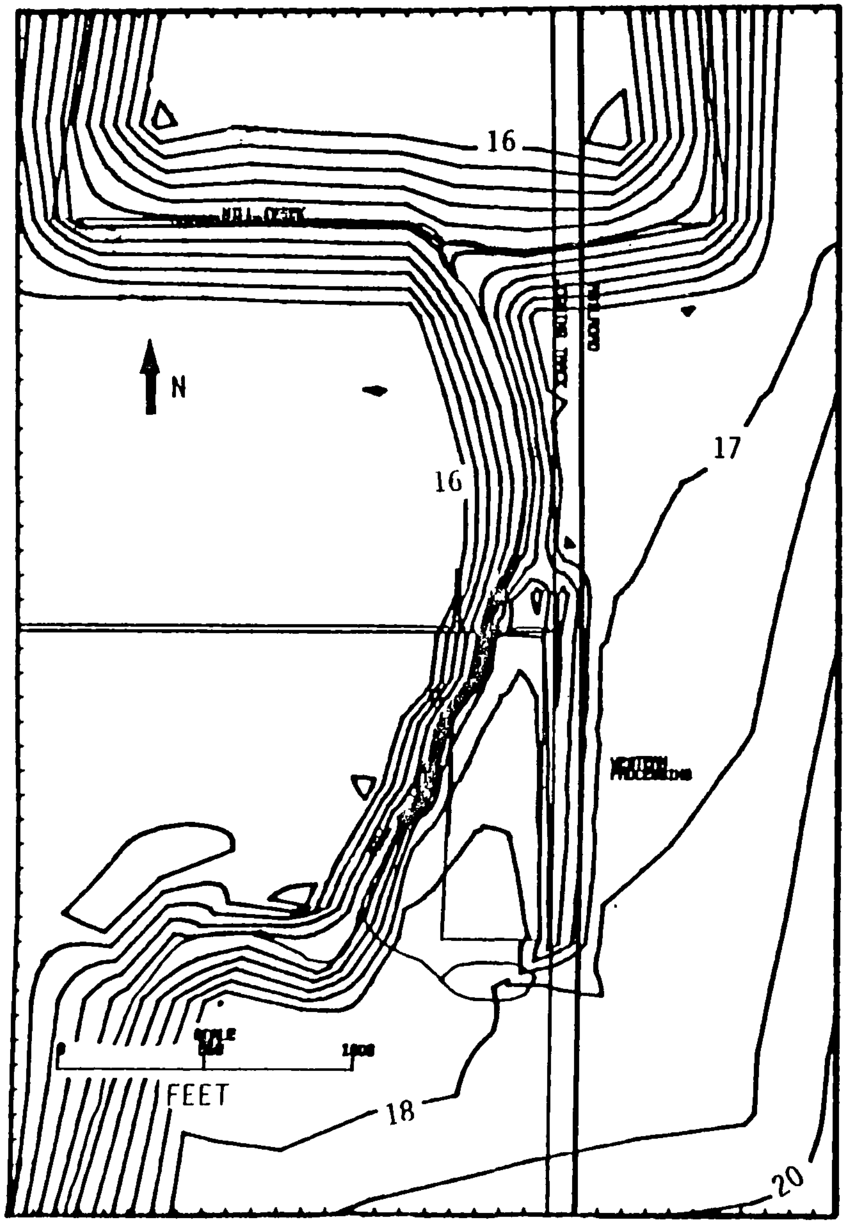


Figure 8. Model-Predicted 1983 Top of Layer 1 Potential Surface for the Base Case Simulation

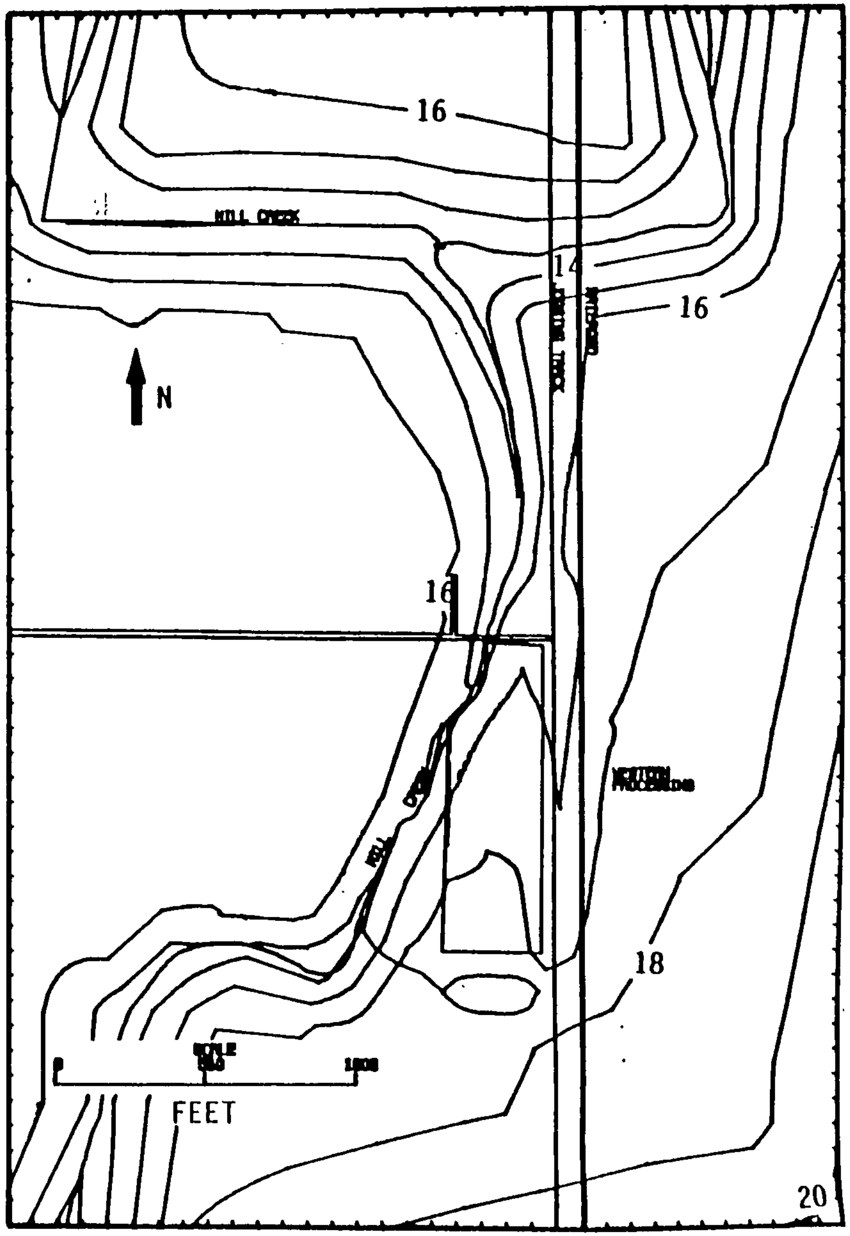


Figure 9. Model-Predicted 1983 Top of Layer 2 Potential Surface for the Base Case Simulation

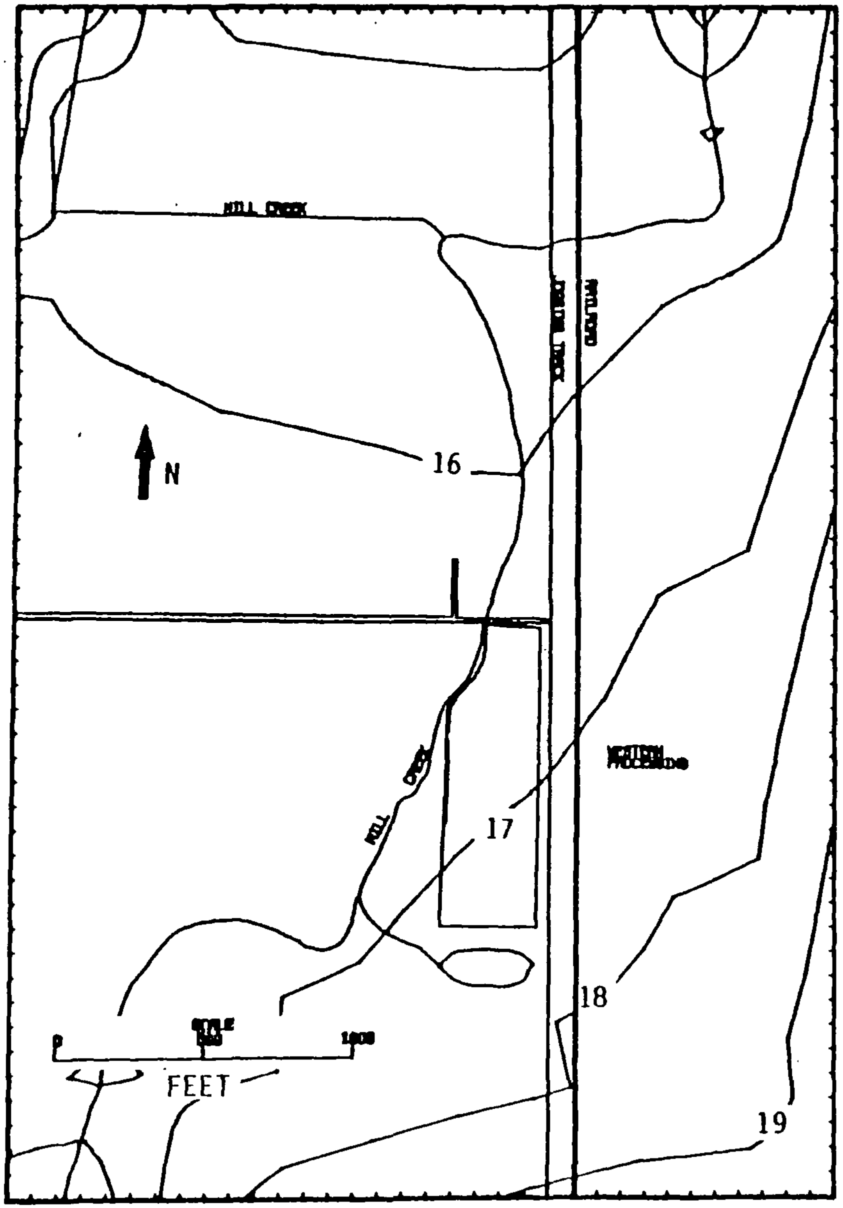


Figure 10. Model-Predicted 1983 Top of Layer 3 Potential Surface for the Base Case Simulation

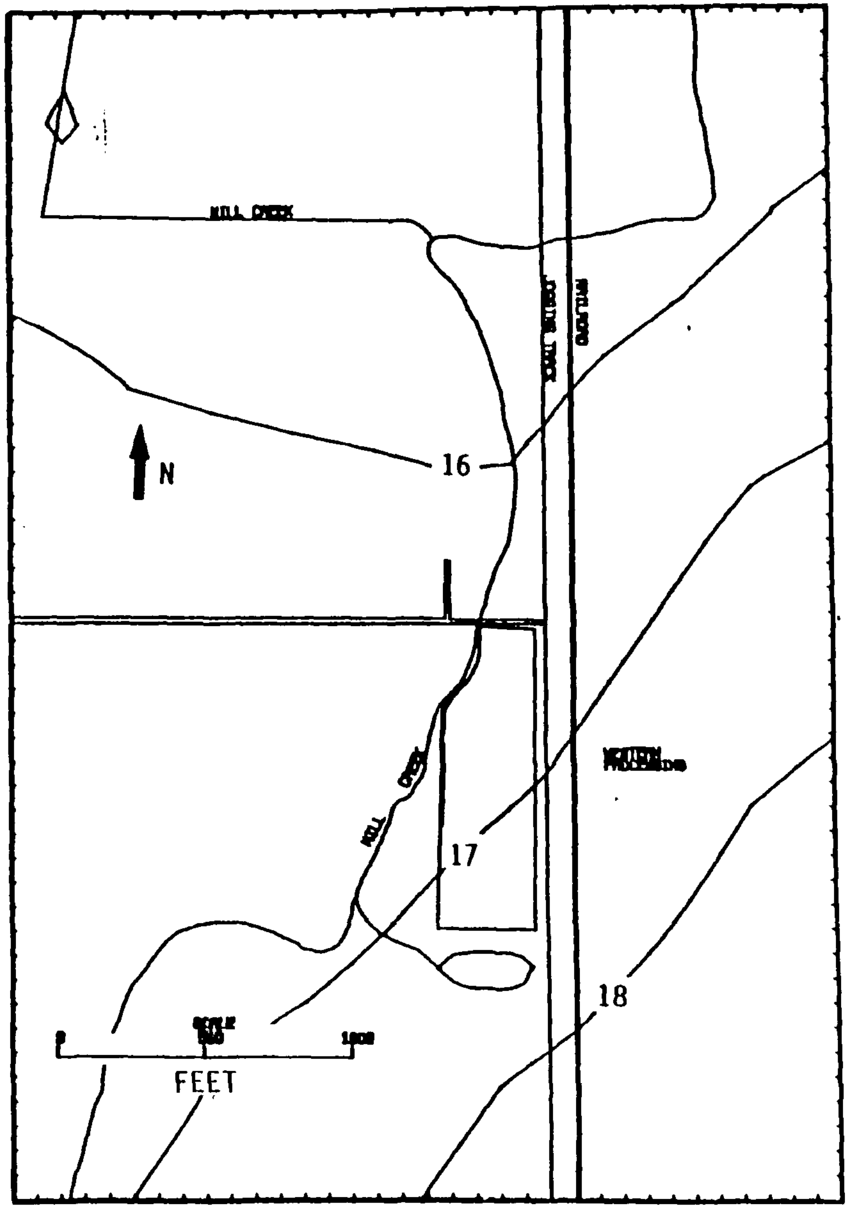


Figure 11. Model-Predicted 1983 Top of Layer 4 Potential Surface for the Base Case Simulation

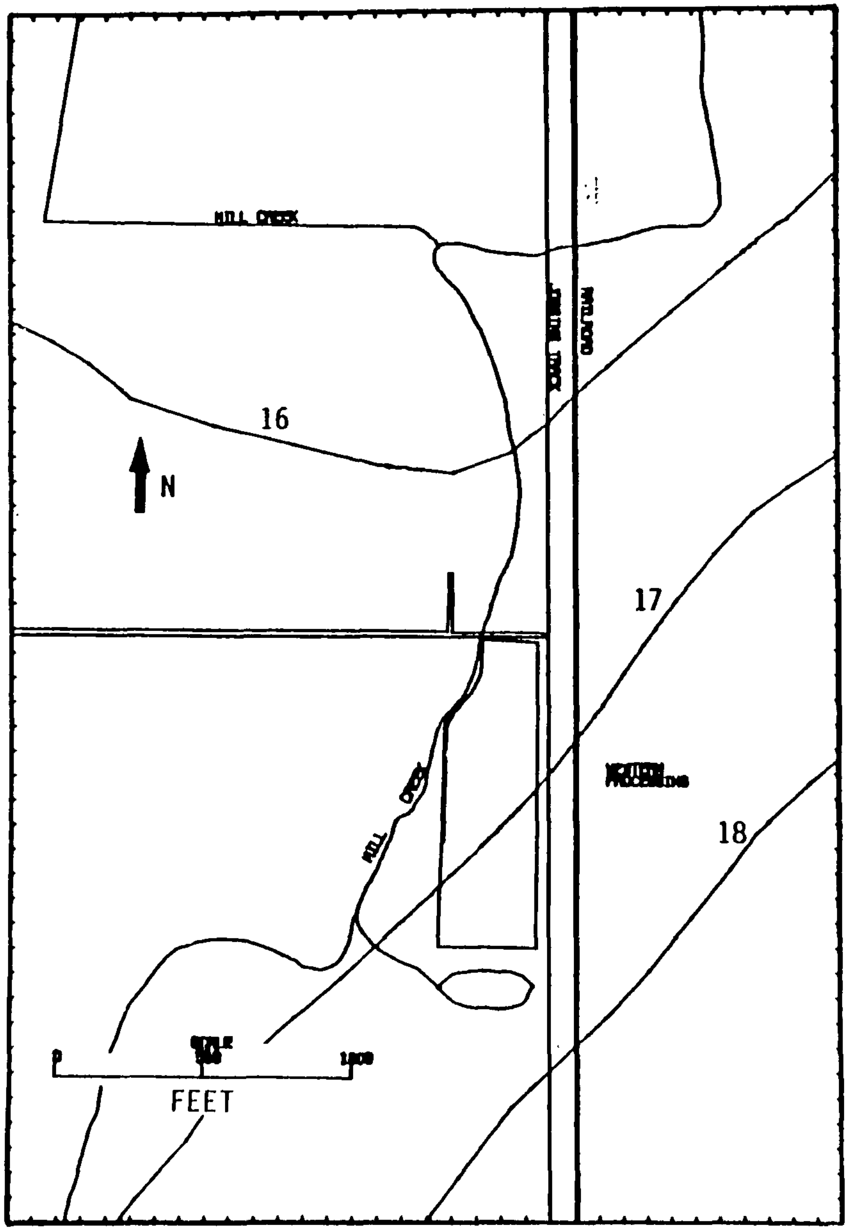


Figure 12. Model-Predicted 1983 Bottom of Layer 4 Potential Surface for the Base Case Simulation.

flow patterns to a depth of about 30 ft (9 m) and its influence can be seen at 100 ft (30 m). The model predicts that regional groundwater flow becomes dominant somewhere between 30 and 50 ft (9 and 15 m) below the surface.

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 1963 to 1983. The model was calibrated by comparing model-predicted to measured TCE concentrations for 1983, TCE mass loading to Mill Creek, and total mass of TCE in the system in 1983.

The difference between model-predicted and measured data was minimized by adjusting the retardation factor and source strengths in the model. 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 soon after disposal.

A smoothed 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) compare 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 important to match the maximum observed TCE concentration at these areas. This match was achieved through source calibration. The measured and model-predicted concentrations at the three source locations are shown in Table 6.

The concentration of TCE in Mill Creek was calculated based on model results and compared to the measured concentration. The model-calculated concentration of 39 ppb based on a creek flow of 15 cfs (0.4 m^3/sec) is comparable to the creek TCE concentration of 15 ppb measured in January 1984, by EPA Region X.

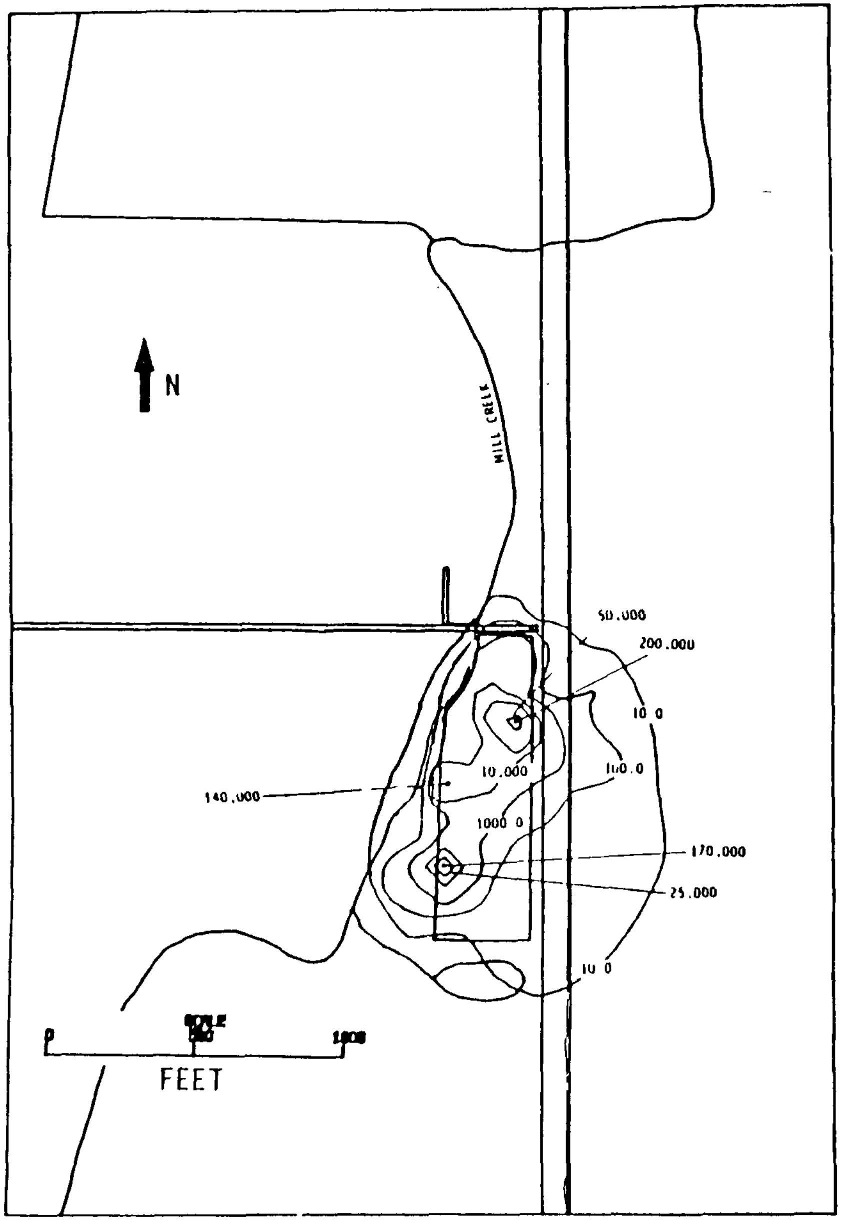


Figure 13. Smoothed Kriged TCE Concentration Contours, Fall, 1982

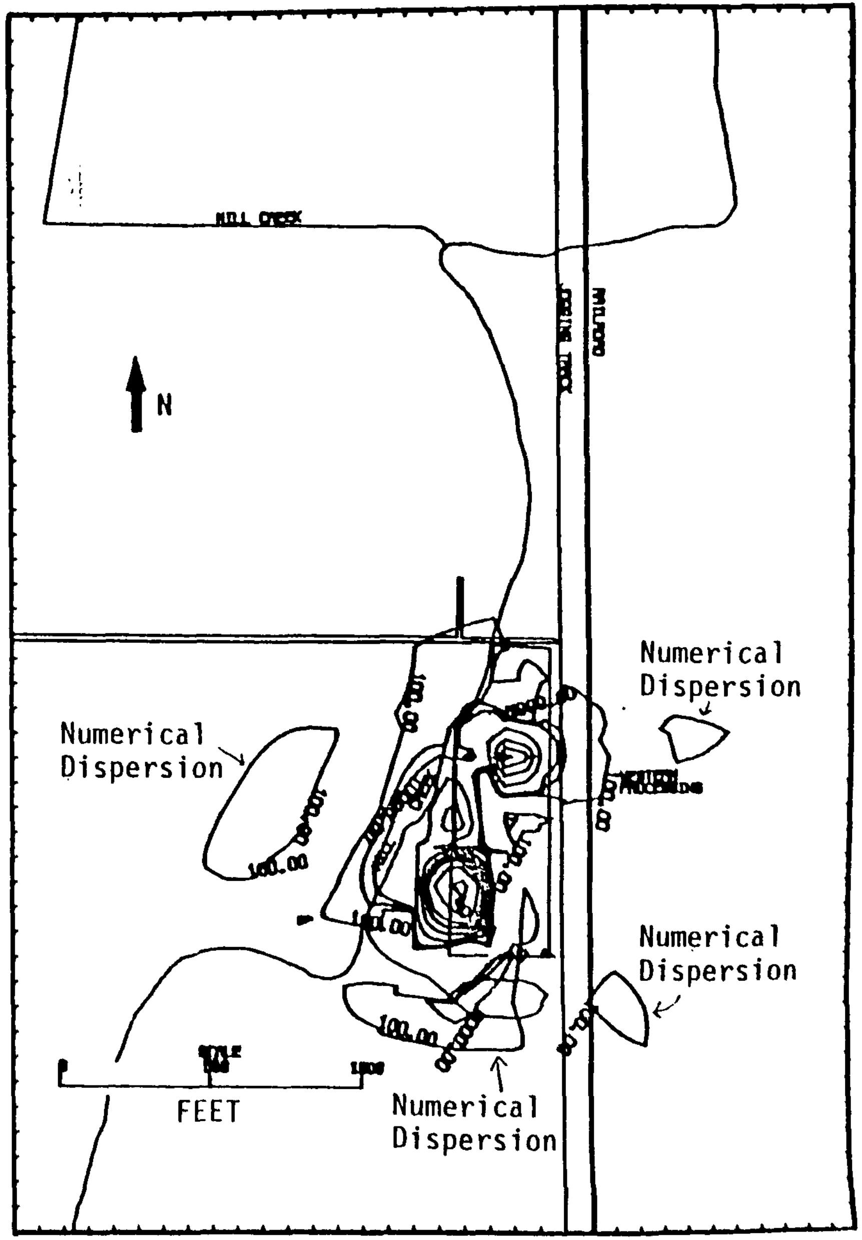


Figure 14. Model-Predicted 1983 Top of Layer 1 TCE Concentration Contours for the Base Case Simulation

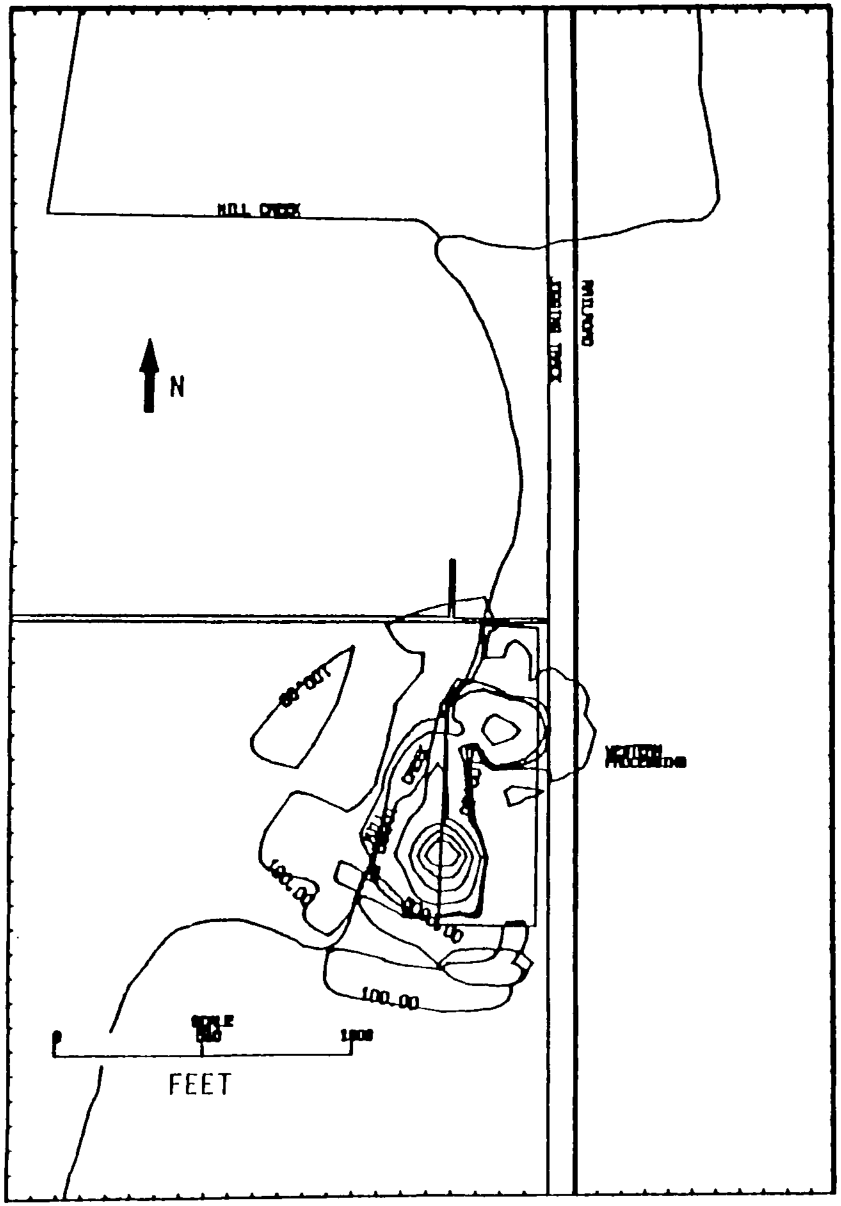


Figure 15. Model-Predicted 1983 Top of Layer 2 TCE Concentration Contours for the Base Case Simulation

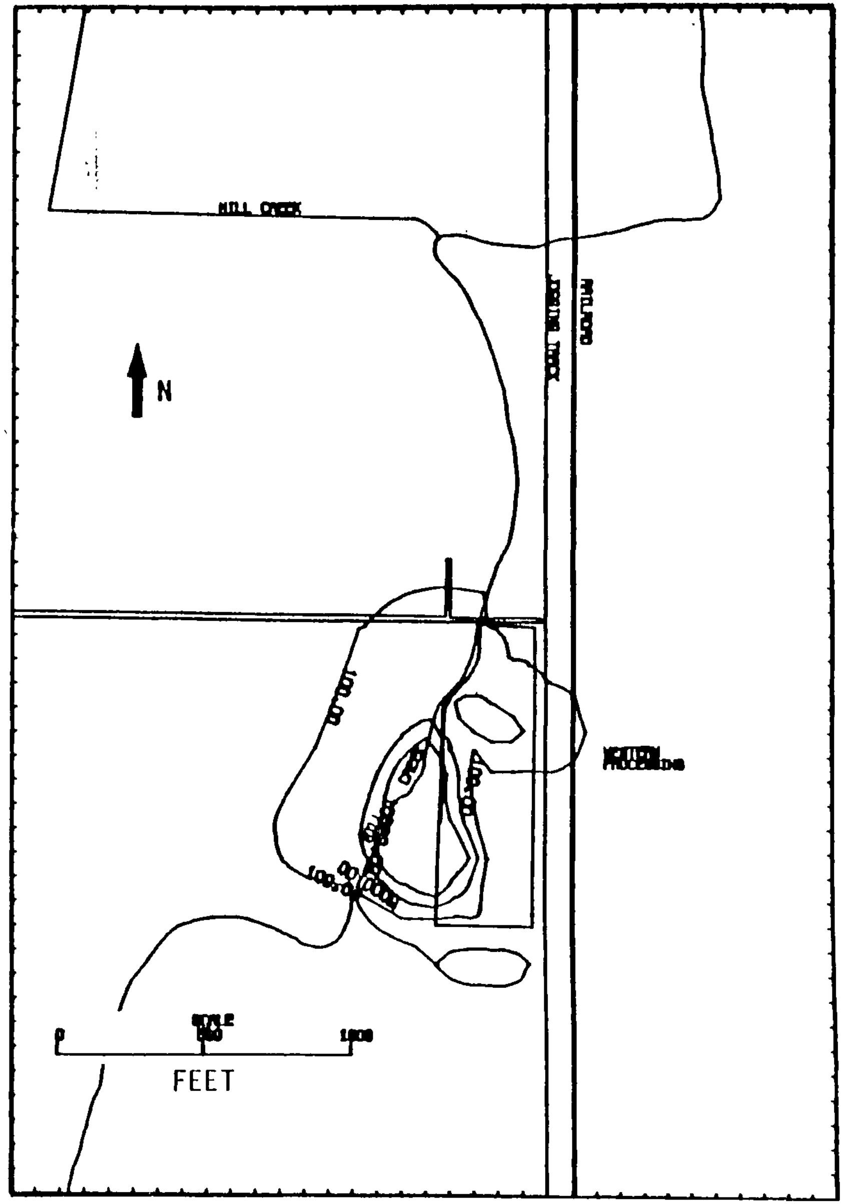


Figure 16. Model-Predicted 1983 Top of Layer 3 TCE Concentration Contours for the Base Case Simulation

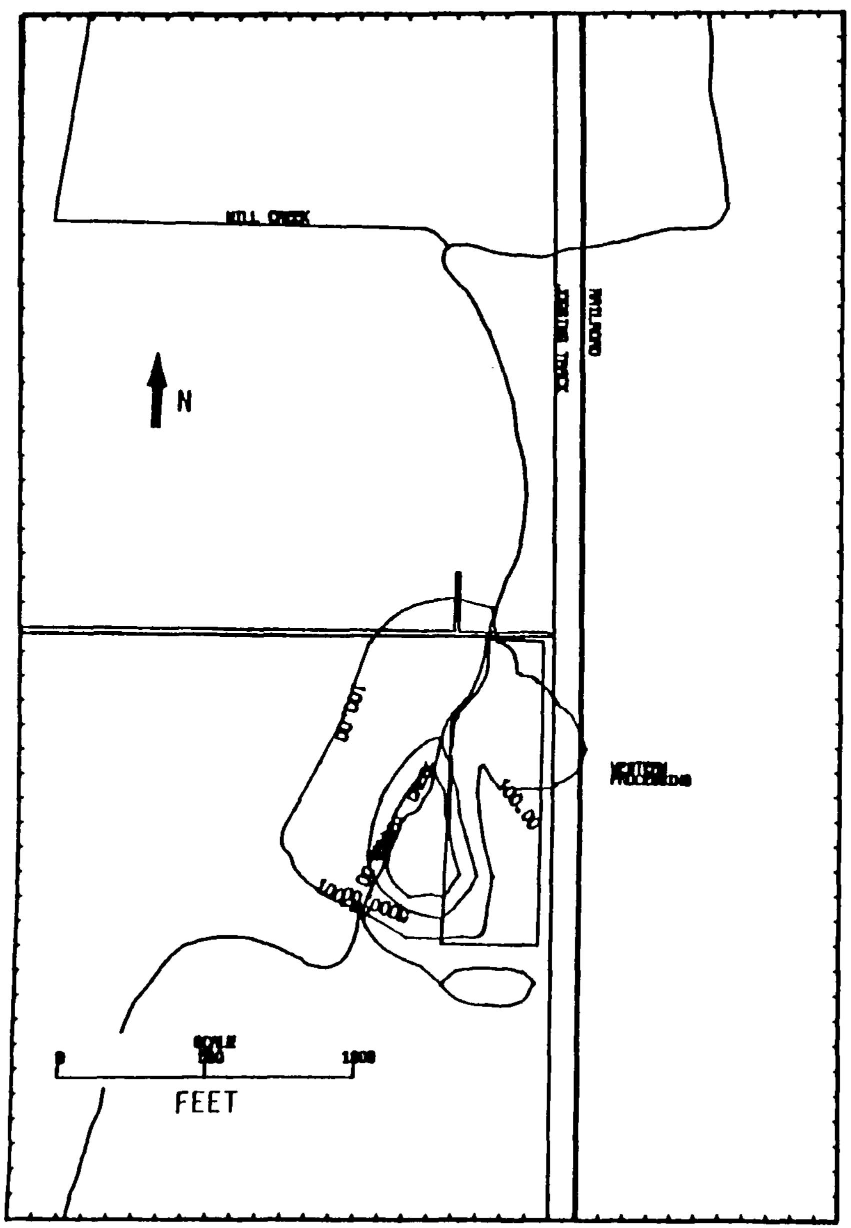


Figure 17. Model-Predicted 1983 Top of Layer 4 TCE Concentration Contours for the Base Case Simulation.

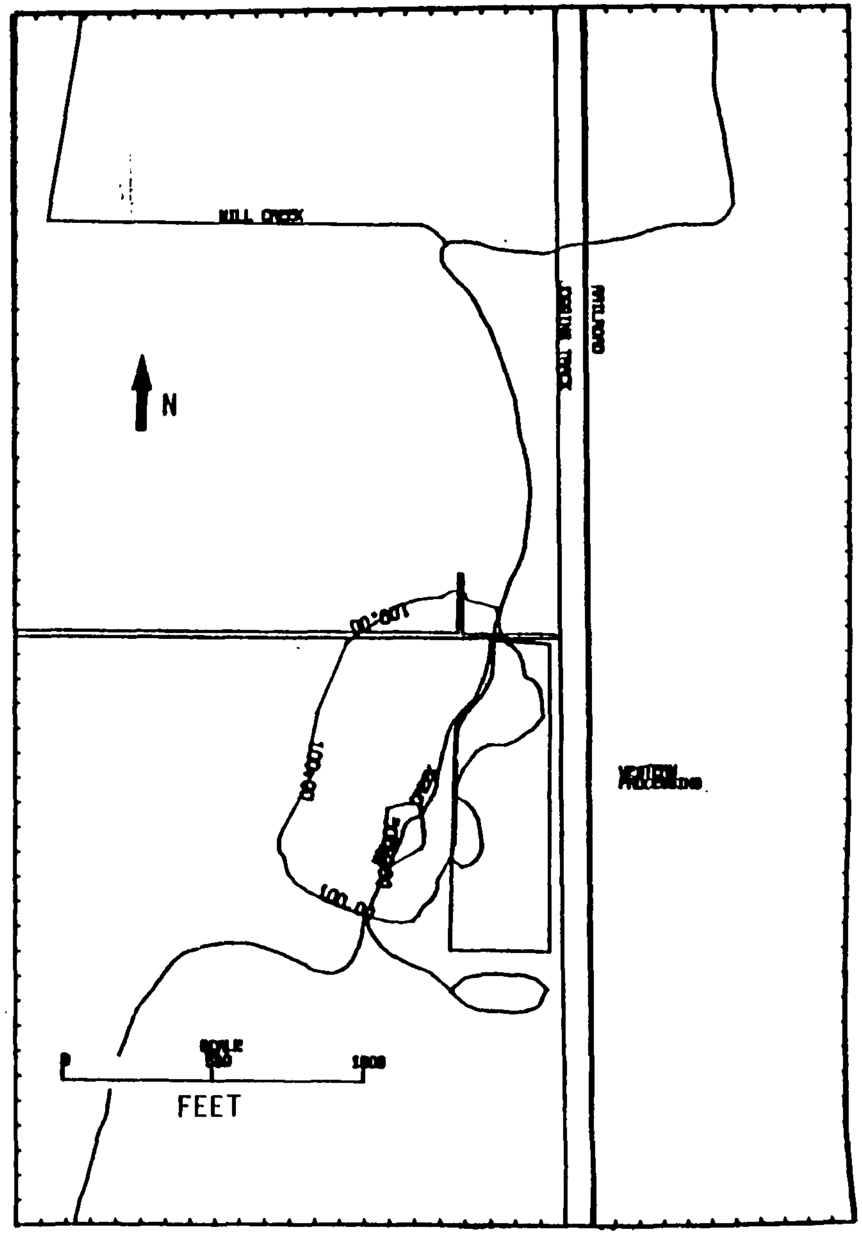


Figure 18. Model-Predicted 1983 Bottom of Layer 4 TCE Concentration Contours for the Base Case Simulation

TABLE 6. COMPARISON OF OBSERVED TO MODEL-PREDICTED MAXIMUM TCE CONCENTRATIONS IN THE GROUNDWATER AT THE THREE SOURCE LOCATIONS

Source Location	Measured Concentration (ppb)	Model-Predicted Concentration (ppb)
Reaction Pond I	210,000	212,000
Reaction Pond III	140,000	139,000
Around Well 21	560,000	557,000

The total mass of TCE (actually TCE plus DCE) in the flow system in 1983 as predicted by the model was 17,100 lb (7,737 Kg). This value compared well with the 18,000 lb (8,144 Kg) of TCE plus DCE as estimated independently by CH2M HILL (1985) and Landau Associates and Dames and Moore (1984) based on the 1982 through 1984 measured concentration data. A list of the parameters used in the final calibrated model is shown in Table 5.

BASE CASE MODEL RESULTS

The base case is defined as the 20-year simulation period from 1963 through 1983. Over this 20-year period, the model predicted that a total of 30,400 lb (13,756 Kg) of TCE entered the groundwater flow system. Of this total, 17,100 lb (7,738 Kg) remained in the flow system in 1983. Of the mass exiting the system 97% (13,300 lb (6,018 Kg)) discharged to Mill Creek and the remaining 3% discharged to the drainage ditch along the eastern boundary of the site. No TCE entered the deeper, regional flow system which flows northwest toward the Green River. The distribution of TCE in the groundwater flow system for the base case is shown in Table 7.

NUMERICAL DISPERSION

Figures 14 and 15 have low concentrations of TCE upgradient from the sources where it is not possible (from the conceptual model) for contamination to have occurred from Western Processing. Occurrences of this phenomena are evidenced by the closed loop 100 ppb contours west of Mill Creek (which is upgradient from the creek in the top three model layers) and south and east of Well 21; these contour lines are identified in Figure 14. In all cases, these upgradient occurrences of TCE are caused by numerical dispersion. Numerical dispersion is inherent to the numerical solution of the convective dispersion equation contained in the model code and, therefore, cannot be avoided. Numerical dispersion can be reduced by adjusting the model node spacing; however, it can never be completely eliminated. In all TCE concentration contour plots (i.e., remedial action simulation plots), upgradient occurrences of TCE have been attributed to numerical dispersion and should be disregarded.

TABLE 7. DISTRIBUTION OF TCE IN THE MODEL BASE CASE SIMULATION

Year	TCE Inflow (lb)	TCE Outflow (lb)	TCE Remaining in Groundwater System (lb)
1968	7,601	1,049	6,552
1973	7,601	2,906	11,247
1978	7,601	4,183	14,655
1983	7,601	5,195	17,071
Total	30,404	13,333	

SECTION 6

SENSITIVITY ANALYSIS

After the model calibration was completed, several additional model runs were made to test the sensitivity of the model results to changes in various model input parameters. The sensitivity runs were performed with the base case model (1963 - 1983) and the base case extended 20 years into the future. Thus, the total simulation period was 40 years (1963 - 2003), and the sensitivity runs were performed for the case where no remedial actions were simulated in the model (base case and no-action case).

The model parameters varied in the sensitivity analysis were hydraulic conductivity, porosity, recharge, retardation, and dispersivity. A summary of the sensitivity runs performed is shown in Table 8. For the most part the sensitivity analysis consisted of doubling and halving each parameter while holding all other parameters constant. A summary of the values of the base case model parameters is shown in Table 5.

The results of all the sensitivity runs are shown in Tables 9 through 12. In all sensitivity runs, the mass of TCE entering the groundwater flow system from the source areas was not changed (the infiltration at the sources was the same as the base case). Table 9 summarizes the mass of TCE exiting the system at each time step (5-year intervals) to Mill Creek and the drainage ditch east of the site. In all cases, virtually all (97%) of the TCE exiting the system goes to Mill Creek. Table 10 summarizes the total mass of TCE remaining in the system at each time step. Table 11 reports the model-predicted TCE concentrations for 1983 at the three source areas, the model-predicted groundwater flux to Mill Creek over the model region, and the concentration of TCE in Mill Creek based on the creek loadings predicted by the model. Table 12 summarizes the percent changes of mass and concentration of TCE based on 1983 results.

TABLE 8. SUMMARY OF SENSITIVITY RUNS

Run Number	Parameter(s) Adjusted
1	For all layers, the K is reduced by 0.5. Layers 1 and 2: Kh = 1.75 ft/day, Kv = 8.75 x 10-2 ft/day. Layers 3 and 4: Kh = 25 ft/day, Kv = 2.5 ft/day.
2	For all layers, the K is doubled. Layers 1 and 2: Kh = 7.0 ft/day, Kv = 0.35 ft/day. Layers 3 and 4: K = 100.0 ft/day, Kv = 10.0 ft/day.
3	The K for all layers is reduced by one-tenth. Layers 1 and 2: Kh = 0.35, Kv = 0.0175. Layers 3 and 4: Kh = 5.0, Kv = 0.5.
4	The K for all layers is increased ten times. Layers 1 and 2: Kh = 35, Kv = 1.75. Layers 3 and 4: Kh = 500, Kv = 50.
5	The effective porosity is reduced by 0.5 for all layers; porosity = 7.5%.
6	The effective porosity is doubled for all layers; porosity = 30%.
7	The recharge is reduced to zero.
8	The recharge is increased to 16 in./yr.
9	The retardation is reduced to zero.
10	The retardation is increased to 8.
11	The dispersivity is reduced by a factor of 5: D_L = 5 ft, D_T = 1 ft.
12	The dispersivity is increased by a factor of 5: D_L = 125 ft, D_T = 25 ft.
13	The effective porosity is 30% for all layers and the retardation is 2.
14	The effective porosity of Layers 1 and 2 is 45% and the porosity of Layers 3 and 4 is 40%.
15	For Layers 3 and 4: Kh = 25 ft/day, Kv = 2.5 ft/day; and porosity = 25%
16	Effective porosity = 25%, retardation = 8.0.

K = hydraulic conductivity

TABLE 9. SUMMARY OF MASS OF TCE (LB) EXITING THE SYSTEM FOR THE SENSITIVITY RUNS

Time Step	Year	Base Case	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
1	1968	1,049	604	1,768	175	4,493	1,859	542	944	1,143
2	1973	2,906	1,823	4,514	632	8,160	4,706	1,655	2,645	3,131
3	1978	4,183	2,770	6,004	1,126	7,508	6,181	2,543	3,847	4,466
4	1983	5,195	3,506	6,836	1,513	7,879	6,949	3,238	4,824	5,491
5	1988	4,971	3,616	5,454	1,676	3,139	5,418	3,375	4,706	5,162
6	1993	3,708	3,045	3,048	1,513	244	2,897	2,877	3,636	3,723
7	1998	2,839	2,689	1,729	1,284	61	1,573	2,560	2,910	2,725
8	2003	2,000	2,419	814	1,130	15	707	2,336	2,192	1,780

Time Step	Year	Base Case	Run 9	Run 10	Run 11	Run 12	Run 13	Run 14	Run 15	Run 16
1	1968	1,049	3,003	542	1,386	810	1,049	350	969	310
2	1973	2,906	6,672	1,655	3,731	2,259	2,097	1,144	2,677	1,029
3	1978	4,183	7,380	2,542	5,003	3,455	4,183	1,857	3,783	1,691
4	1983	5,195	7,404	3,238	5,848	4,402	5,194	2,412	4,655	2,202
5	1988	4,971	4,759	3,375	5,245	4,281	4,971	2,602	4,453	2,373
6	1993	3,708	1,621	2,878	3,501	3,407	3,709	2,293	3,428	2,100
7	1998	2,839	720	2,560	2,681	2,596	2,839	2,059	2,893	1,869
8	2003	2,000	140	2,336	2,029	1,860	1,999	1,946	2,405	1,762

TABLE 10. SUMMARY OF TOTAL MASS OF TCE (LB) IN THE GROUNDWATER SYSTEM FOR THE SENSITIVITY RUNS

Time Step	Year	Base Case	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
1	1968	6,552	6,997	5,833	7,426	3,108	5,742	7,059	6,657	6,458
2	1973	11,247	12,775	8,920	14,395	2,549	8,637	13,005	11,613	10,928
3	1978	14,665	17,606	10,517	20,870	2,642	10,057	18,063	15,367	14,063
4	1983	17,071	21,701	11,282	26,958	2,364	10,709	22,426	18,144	16,173
5	1988	13,075	19,070	6,803	26,057	0	6,266	20,026	14,413	11,986
6	1993	9,611	16,269	3,999	24,788	0	3,613	17,393	11,021	8,507
7	1998	6,833	13,641	2,331	23,565	0	2,101	14,894	8,172	5,843
8	2003	4,848	11,237	1,532	22,450	0	1,409	12,573	5,995	4,078

Time Step	Year	Base Case	Run 9	Run 10	Run 11	Run 12	Run 13	Run 14	Run 15	Run 16
1	1968	6,552	4,598	7,059	6,215	6,791	6,552	7,251	6,632	7,292
2	1973	11,247	5,527	13,005	10,085	12,133	11,246	13,708	11,556	13,864
3	1978	14,665	5,748	18,064	12,683	16,279	14,664	19,452	15,374	19,774
4	1983	17,071	5,945	22,427	14,436	19,478	17,071	24,641	18,320	25,173
5	1988	13,075	2,161	19,827	9,966	15,972	12,875	22,814	14,842	23,774
6	1993	9,611	784	17,193	6,709	12,809	9,410	20,765	11,658	21,918
7	1998	6,833	125	14,694	4,089	10,274	6,632	18,767	8,826	20,104
8	2003	4,848	0	12,373	2,075	8,429	4,648	16,836	6,436	18,354

TABLE 11. TCE CONCENTRATION (PPB) AT THE SOURCES IN 1983 FOR THE SENSITIVITY RUNS

Location	Base Case	Run 1	Run 2	Run 3	Run 4	Run 5
Reaction Pond I	212,000	315,000	121,000	441,000	21,000	218,000
Reaction Pond III	139,000	232,000	72,000	403,000	10,000	132,000
Well 21	557,000	700,000	368,000	822,000	80,000	620,000
Mill Creek	39	27	51	11	60	52
Groundwater Flux into Mill Creek (cfs)	0.45	0.23	0.90	0.05	4.42	0.45

Location	Base Case	Run 6	Run 7	Run 8	Run 9	Run 10
Reaction Pond I	212,000	184,000	207,000	213,000	207,000	184,000
Reaction Pond III	139,000	133,000	161,000	120,000	117,000	133,000
Well 21	557,000	448,000	718,000	416,000	622,000	448,000
Mill Creek	39	24	36	41	56	24
Groundwater Flux into Mill Creek (cfs)	0.45	0.45	0.44	0.46	0.45	0.45

Location	Base Case	Run 11	Run 12	Run 13	Run 14	Run 15	Run 16
Reaction Pond I	212,000	485,000	53,000	212,000	160,000	212,000	154,000
Reaction Pond III	139,000	222,000	50,000	139,000	122,000	144,000	119,000
Well 21	557,000	911,000	207,000	557,000	373,000	538,000	354,000
Mill Creek	39	43	33	38	18	34	16
Groundwater Flux into Mill Creek (cfs)	0.45	0.45	0.45	0.45	0.45	0.42	0.45

TABLE 12. PERCENT CHANGE OF MASS AND CONCENTRATION OF TCE FOR THE SENSITIVITY RUNS BASED ON 1983 RESULTS

Run No.	Mass Exiting	Total Mass in System	Reaction Pond I	Reaction Pond III	Well 21	Mill Creek	Mill Creek Flux
1	-33	+27	+49	+67	+26	-31	-49
2	+32	-34	-43	-48	-34	+31	+100
3	-71	+58	+108	+190	+48	-72	-89
4	+52	-86	-90	-93	-86	+54	+882
5	+34	-38	+3	-5	+11	+33	0
6	-38	+31	+13	-4	-20	-38	0
7	-7	+6	-2	+16	+29	-8	-2
8	+6	-5	0	-13	-25	+5	+2
9	+43	-65	-2	-16	+12	+44	0
10	-38	+31	-13	-4	-20	-38	0
11	+13	-15	+129	+60	+64	+10	0
12	-15	+14	-75	-64	-63	-15	0
13	0	0	0	0	0	0	0
14	-54	+44	-25	-12	-33	-54	0
15	-10	+7	0	+4	-3	-13	-7
16	-58	+47	-27	-14	-36	-58	0

+ = increase

- = decrease

A discussion of the results shown in the tables and a summary of all the sensitivity analysis model runs is presented below.

HYDRAULIC CONDUCTIVITY (RUNS 1 - 4)

Four sensitivity runs were made where the base case horizontal and vertical hydraulic conductivities (K) were changed by factors of 0.1, 0.5, 2.0, and 10.0. Decreasing K decreased the groundwater flux through the system which:

1) decreased the TCE mass loading to the creek and ditch;
2) increased the total mass of TCE in the system;
3) increased the concentration of TCE at the three source areas; and
4) decreased the groundwater flux to Mill Creek.

Increasing K increased the flux through the system which had the opposite effect of decreasing K as discussed above.

Decreasing the K by factors of 2.0 and 10.0 increased the water table elevation over the model region by about 1.0 and 5.0 ft (0.3 and 1.5 m), respectively. Increasing the K by a factor of 10.0 decreased the potentials by about 0.5 ft (0.15 m), whereas increasing K by a factor of 2.0 only slightly decreased the potentials.

POROSITY (RUNS 5 AND 6)

Two sensitivity runs were made where the base case effective porosity was changed by factors of 0.5 and 2.0. Decreasing the effective porosity increased the groundwater velocity and decreased the amount of dilution. The effect of this change was to:

1) increase the mass loading to the creek and ditch;
2) decrease the total mass in the system;
3) increase the concentration at 2 of the 3 source areas (Reaction Pond III decreased slightly); and
4) maintain the same groundwater flux to the creek.

Increasing the porosity had the opposite effect of decreasing the porosity. Changes in porosity had no impact on the groundwater potentials.

DISPERSIVITY (RUNS 11 AND 12)

Two sensitivity runs were made where the base case longitudinal and transverse dispersivity were changed by factors of 0.2 and 5.0. Decreasing the dispersivity:

1) increased the mass loading to the creek and ditch;
2) decreased the total mass in the system;
3) increased the concentration at the three source areas; and
4) did not impact the groundwater flux to the creek.

Increasing the dispersivity had the opposite effect of decreasing it.

Changes in dispersivity had no impact on the groundwater potentials.

COMBINATION RUNS (RUNS 13 - 16)

Four runs were made in which either two parameters were changed simultaneously or a single parameter was varied between layers.

In Run 13 the effective porosity was doubled and the retardation factor was halved. These parameters both impact the groundwater velocity and the changes offset each other, therefore, the results are virtually identical to the base-case results.

In Run 14 the effective porosity in the upper and lower units was increased to 45% and 40%, respectively. The impact of this increase is similar to the impact of increasing porosity as discussed above.

In Run 15 the hydraulic conductivity in the lower unit (model Layers 3 and 4) was halved and the effective porosity in the lower unit was increased to 25%. The impact of these changes was to:

1) decrease the mass loading to Mill Creek;
2) increase the total mass in the system; and
3) decrease the groundwater flux to Mill Creek.

The change in concentration and flux was small. The parameter changes made only in Unit 2 (gravelly sand) changed the model results slightly (Table 12), indicating that some contaminant is migrating through the lower unit of the model to Mill Creek.

In Run 16 the effective porosity in all layers was increased to 25% and the retardation was increased to 8.0. This case was intended to better match the parameters used by CH2M HILL in their feasibility study. The effect of these changes was to:

1) decrease the mass loading to the creek and ditch;
2) increase the total mass in the system;
3) decrease the concentrations at the three source areas; and
4) maintain the base case flux rate to Mill Creek.

The groundwater potential surfaces were virtually unchanged by the changes made in the combination runs.

SENSITIVITY ANALYSIS SUMMARY

Only three of the sensitivity runs showed significant changes in the potential surfaces: those where the K was decreased by factors of 2.0 and 10.0, and where the recharge was doubled. The potential surfaces for the top of Layer 1 for the case where K was decreased by a factor of 10.0 is shown in Figure 19. The potential surface for the case where the K decreased a factor of 2.0 and for the case where recharge was doubled are virtually the same and are shown in Figure 20.

Changing the hydraulic conductivities changes the groundwater flux through the system as well as the velocity, whereas changing the porosity or retardation factor only impacts the velocity of the contaminant. Changing recharge has a small impact on groundwater flux, whereas dispersivity has no impact on flux. Therefore, the groundwater flux to Mill Creek is almost completely controlled by the hydraulic conductivity. Since the base case model accurately predicts the measured value of groundwater flux to Mill Creek over the model region the hydraulic conductivity used in the model is probably reasonable.

The mass of TCE exiting the system is about equally controlled by the hydraulic conductivity, the porosity, and the retardation factor. If any one of these parameters is changed by a factor of two, the results are altered by a factor of about plus or minus 35%. This degree of sensitivity supports the values currently used in the model.

Dispersivity has the greatest influence on concentration at the three source areas. Dispersivity is also the parameter in which we have the least confidence. The other parameter which influences the source concentrations, is the hydraulic conductivity. Changes in porosity, retardation, and recharge have little influence on the concentrations at the sources. Since

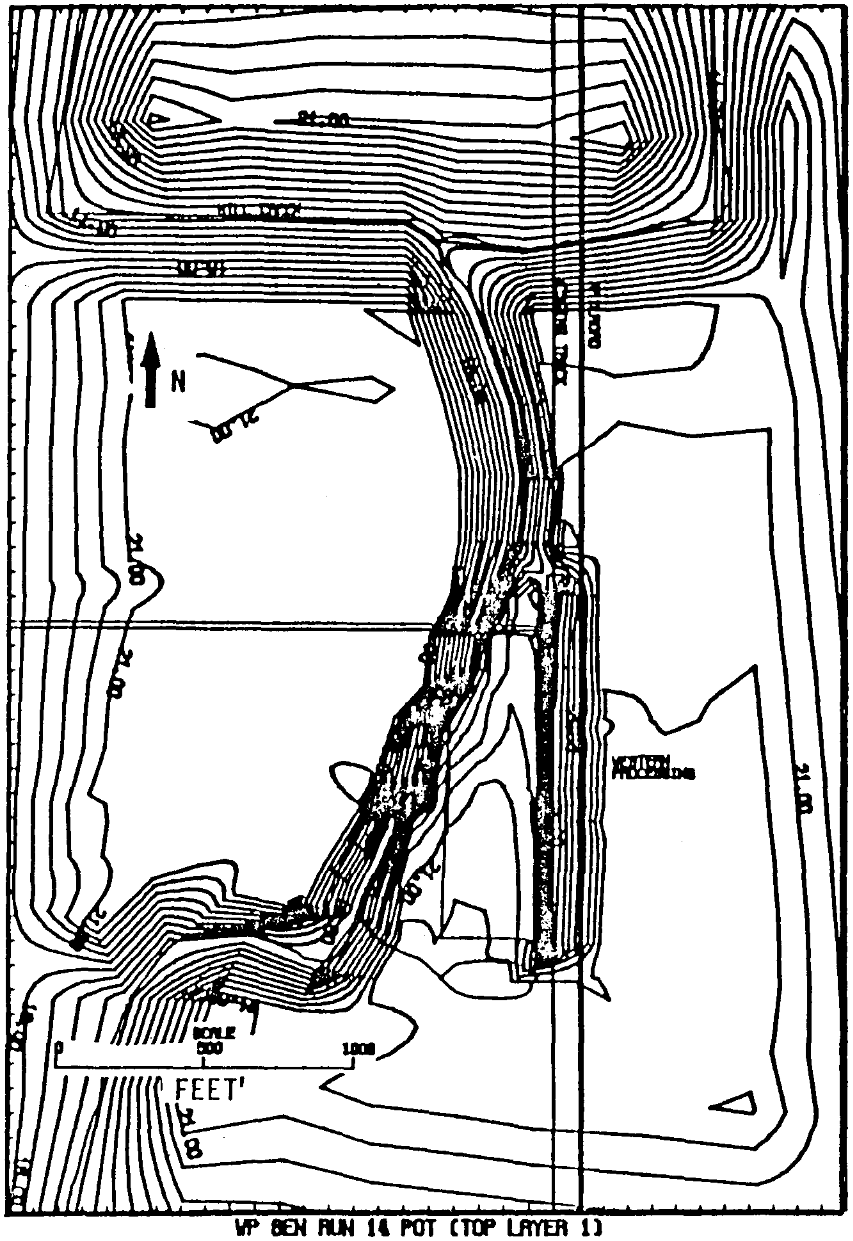


Figure 19. Model-Predicted Top of Layer 1 Potential Surface for the Sensitivity Run with One-Tenth the Hydraulic Conductivity

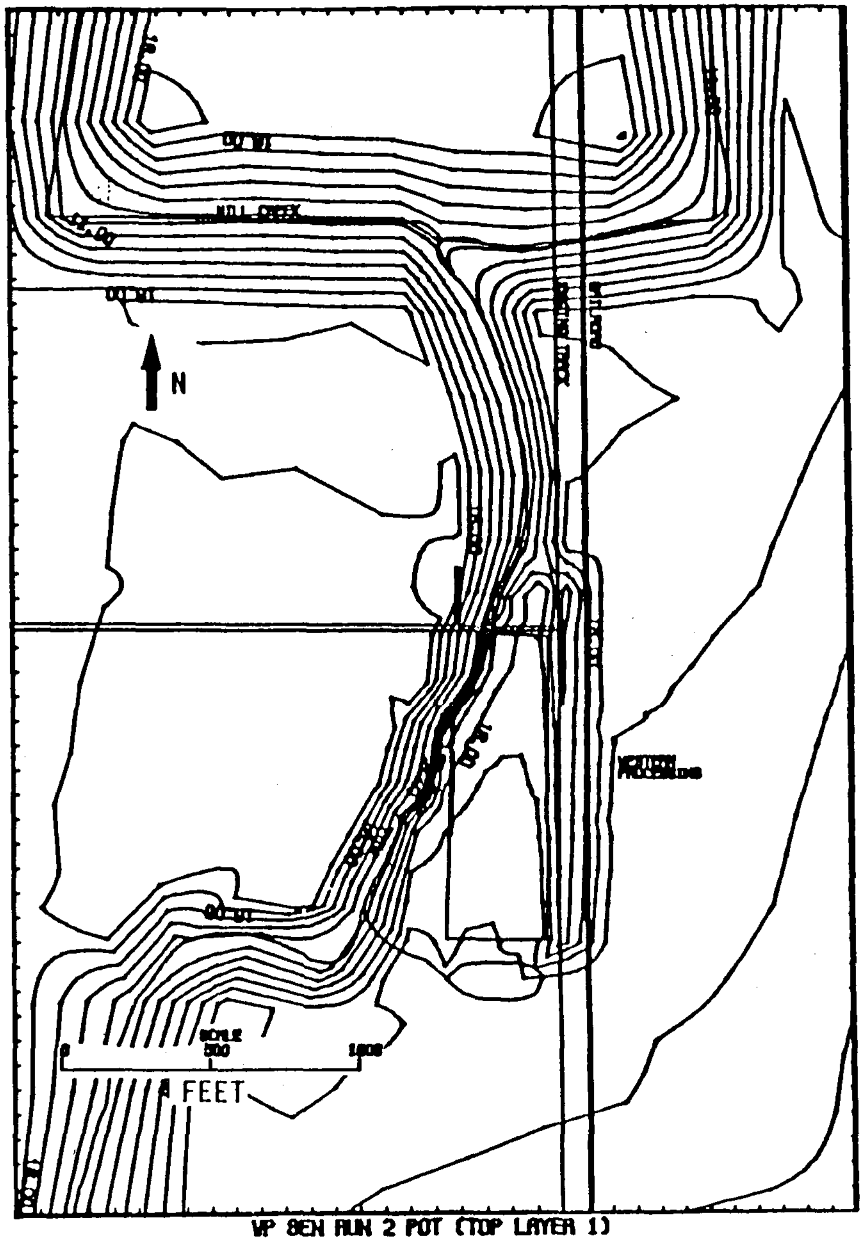


Figure 20. Model-Predicted Top of Layer 1 Potential Surface for the Sensitivity Run with One-Half the Hydraulic Conductivity and the Sensitivity Run with Double the Recharge

dispersivity is the primary factor controlling source concentration, and the model-predicted concentrations match the measured values, the base case dispersivity is probably reasonable.

The limited sensitivity analysis illustrated how every parameter has some influence on the groundwater potential, the flow to Mill Creek, the TCE flux to Mill Creek, and/or the total mass of TCE in the system. Changing any of the parameters will affect the current calibration.

SECTION 7

ASSESSMENT OF REMEDIAL ACTION ALTERNATIVES

Remedial action alternatives for the Western Processing Site have been proposed by CH2M HILL and the PRPs for site restoration. The purpose of the remedial action assessment performed in this study was to simulate these proposed alternatives in the final calibrated model in order to evaluate and compare their effectiveness.

The base case consisted of running the final calibrated model for 20 years, from 1963 through 1983. In order to simulate the remedial action alternatives, certain model parameters were adjusted in 1983 and the model was run for an additional 50 years to the year 2033. When the pump and treat alternative was simulated, water was withdrawn for the first 30 years (1983 - 2013) in the CH2M HILL cases and for the first 5 years (1983 - 1988) in the PRPs cases. The model results during the prediction period were used to determine which action would be most effective in reducing the level of contamination at the site.

The following section describes the remedial action alternatives and how they were simulated in the model, and provides the results of each simulation. The alternatives are discussed in two sections, those proposed by CH2M HILL and those derived from the alternative proposed by the PRPs. A summary of the results is also provided in Section 2.

CH2M HILL PROPOSED REMEDIAL ACTIONS

CH2M HILL requested that three basic simulations be performed with the model:

1) no-action;
2) source removal combined with pump and treat; and
3) cap combined with pump and treat.

The pump and treat cases were run with two different pumping rates. In order to better understand the results, a simulation involving source removal only was also performed. These three cases and variations are discussed below.

<u>No Action (Extension of the Base Case)</u>

The no-action simulation consisted of running the base case model (final calibrated model presented earlier) 50 years into the future. The purpose of this simulation was to determine the predicted extent of TCE contamination if no remedial measures are implemented at the site. This simulation served as a benchmark against which the CH2M HILL proposed remedial actions could be compared.

The potential surfaces for the no-action case are the same as for the base case (Figures 8 to 12). TCE concentration contours at the top of Layer 1 in the years 1993, 2003, and 2033 (10, 20, and 50 years into the future) are shown in Figures 21 through 23, respectively. The total mass of TCE in the flow system, and the total mass of TCE discharging to Mill Creek and the drainage ditch over 5 year intervals are shown in Table 13.

Table 13 shows that of the 31,699 lb (14,378 Kg) that entered the groundwater flow system between 1963 and 2003, 15% and 4% remain in the system in the years 2003 and 2033 (20 and 50 years in the future), respectively. Of the 17,071 lb (7,743 Kg) remaining in the flow system in 1983, about 88% and 99% discharges to Mill Creek and the ditch by the years 2003 and 2033, respectively. As for the base case, about 97% of the TCE exiting the system discharges to Mill Creek and the remaining 3% discharges to the ditch.

<u>Source Removal</u>

The source removal action assumes that 6 ft (2 m) of unsaturated material is excavated and removed from the site. The effect of this action would be to remove the source of TCE that leaches from the unsaturated zone into the saturated flow system.

Source remova' was simulated in the model by eliminating further input of TCE beyond 1983. Because Reaction Pond I is the only source that contributes TCE to the system after 1983 (see Appendix A), source removal was accomplished in the model by eliminating this source after 1983.

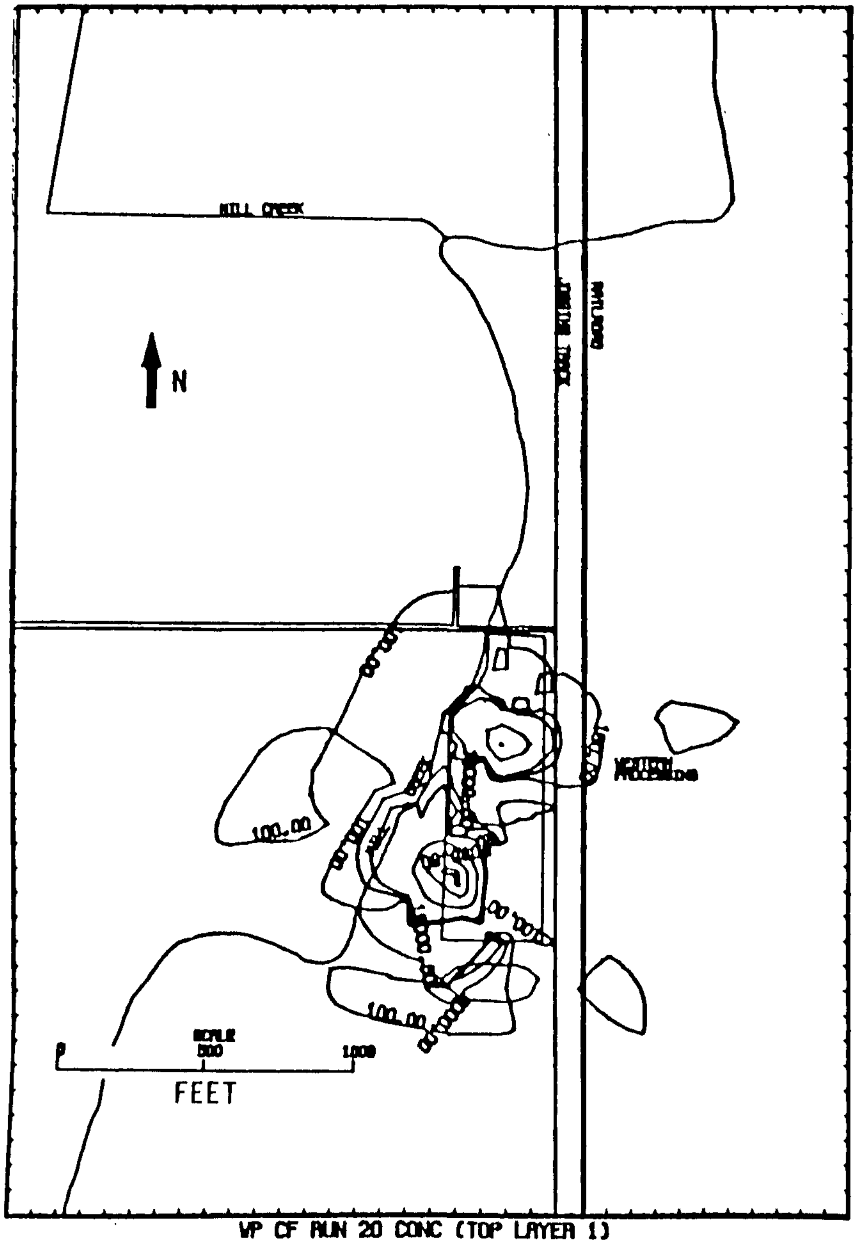


Figure 21. Model-Predicted 1993 Top of Layer 1 TCE Concentration Contours for the No-Action Simulation

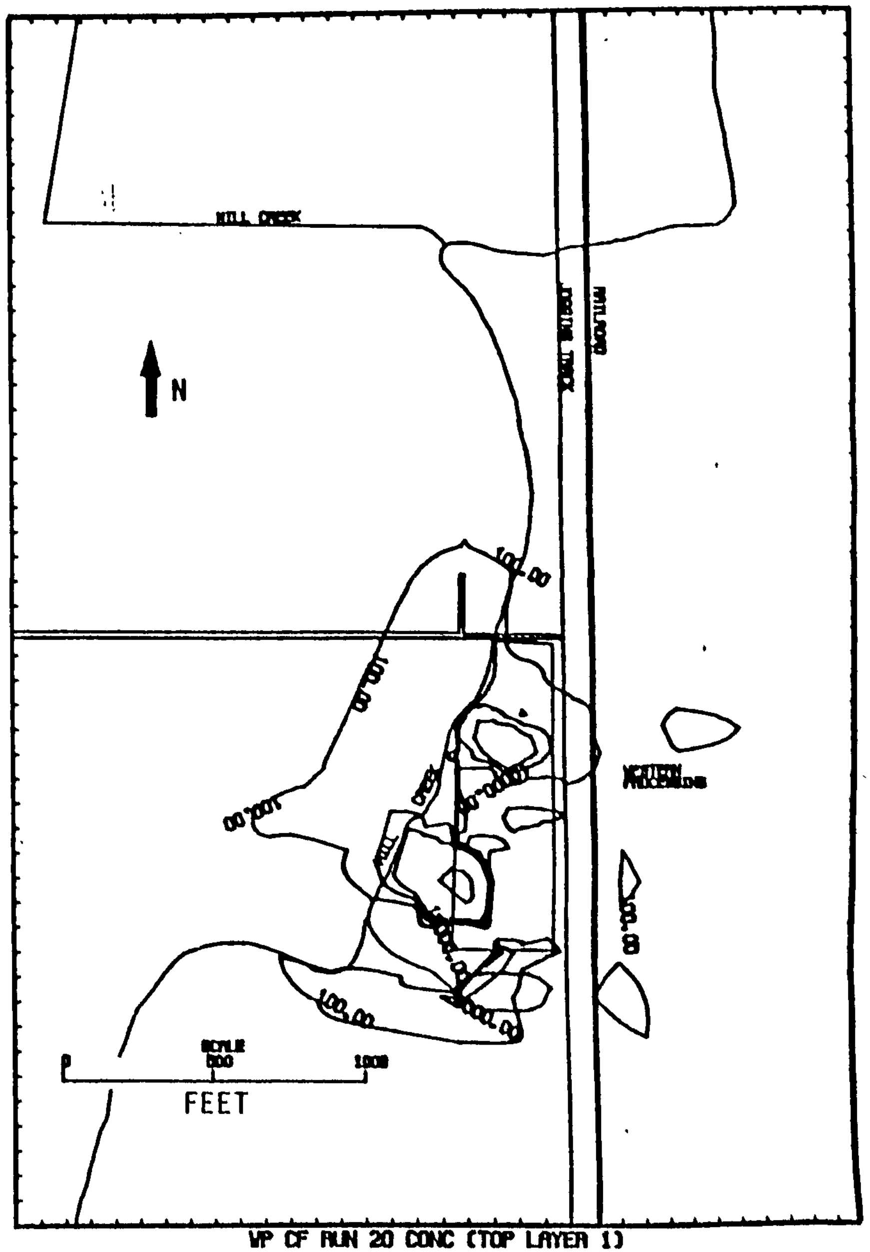


Figure 22. Model-Predicted 2003 Top of Layer 1 TCE Concentration Contours for the No-Action Simulation

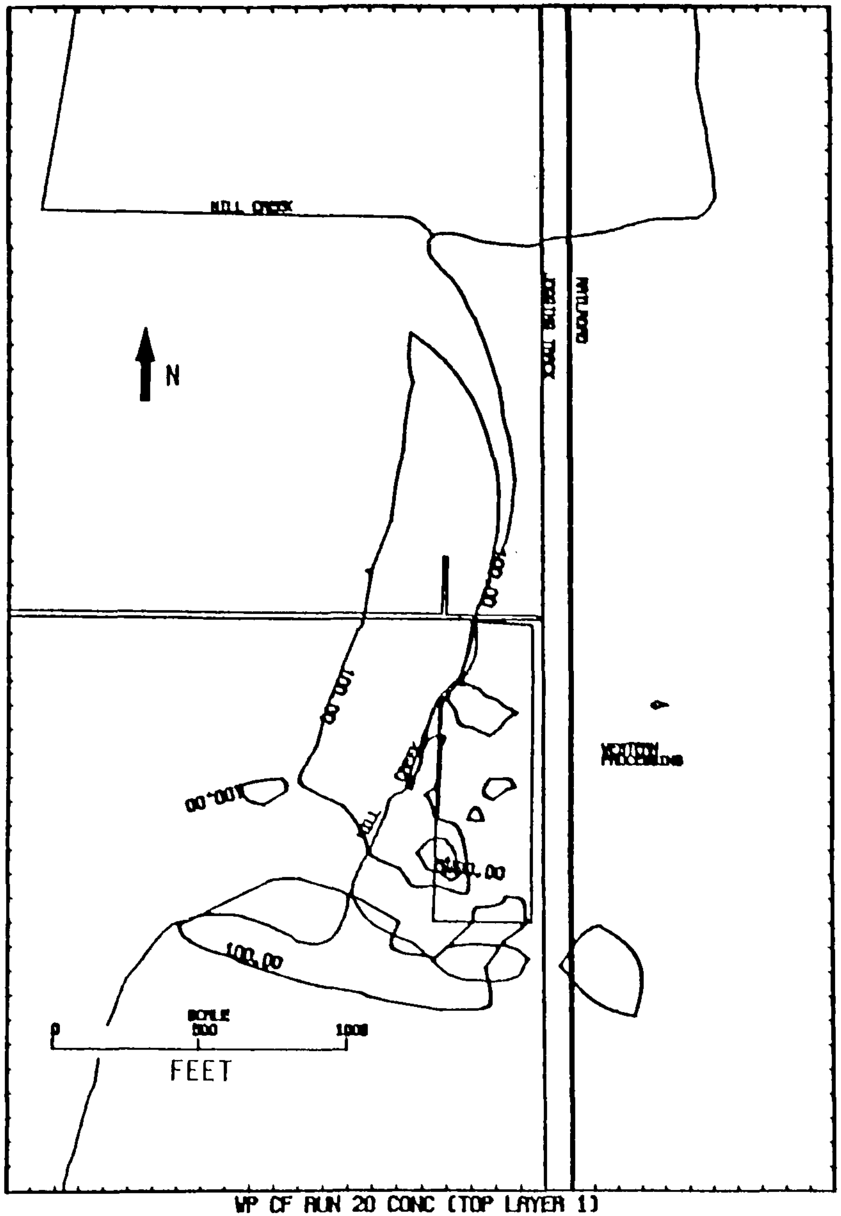


Figure 23. Model-Predicted 2033 Top of Layer 1 TCE Concentration Contours for the No-Action Simulation

TABLE 13. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE CH2M HILL NO-ACTION SIMULATION

Time Step	End Year	TCE Inflow (lb)	TCE Outflow (lb)	Total TCE in System (lb)
1*	1968	7,601	1,049	6,552
2*	1973	7,601	2,906	11,247
3*	1978	7,601	4,183	14,665
4*	1983	7,601	5,195	17,071
5	1988	975	4,971	13,075
6	1993	244	3,708	9,611
7	1998	61	2,839	6,833
8	2003	15	2,000	4,848
9	2008	0	1,288	3,560
10	2013	0	824	2,736
11	2018	0	531	2,205
12	2023	0	379	1,826
13	2028	0	290	1,536
14	2033	0	240	1,296
Total		31,699	30,403	

*Base case

Inflow is mass entering the groundwater flow system and outflow is the mass exiting the system.

The groundwater potential surfaces for the source removal case are identical to those for the base case (Figures 8 to 12) because the soil below the water table was undisturbed. The source removal action removes so little mass of TCE from the system, that the TCE concentration contour plots are essentially the same as those for the no-action case (Figure 21 through 23).

The total mass of TCE in the flow system, and the total mass of TCE discharging to Mill Creek and the ditch over five-year intervals are shown in Table 14. The source removal action removes about 1,300 lb (588 Kg) of TCE from the groundwater flow system. This action results in a slight reduction in the mass of TCE remaining in the system and exiting to the creek and ditch.

The source removal action is not effective in cleaning up the site because most of the TCE has entered the saturated flow system by 1983.

Source Removal Combined with Pump and Treat (100 gpm)

This remedial action assumes that the entire site is excavated to a depth of 6 ft (2 m) (source removal) followed by the withdrawal of contaminated groundwater (pump and treat).

The source removal portion of this alternative was simulated in the model as discussed above. Pumping and treatment was simulated in the model by withdrawing water from a system of 38 wells spaced across the area of the site. Nodes of the finite element grid (Figure 6) were used to represent wells, and the wells were situated in 3 rows running north - south along the east, central, and west portions of the site. It was assumed that the wells were drilled to a depth of 30 ft below the water table and that the total withdrawal rate was 100 gpm (379 l/min) (2.6 gpm (10 l/min) from each well). Pumping was simulated for the first 30 years of the 50 year prediction period.

The potential surface for the top of Layer 1 for this case is shown in Figure 24. The average drawdown over the site due to pumping was about 4 ft (1.2 m).

The total mass of TCE in the flow system, and the total mass discharging to Mill Creek and the pumping wells over 5-year intervals are shown in Table 15. The model results show that 91% of the TCE is removed from the flow system in the first 5 years, and that all the TCE is removed in 15

TABLE 14. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE CH2M HILL SOURCE REMOVAL ACTION

Time Step	End Year	TCE Inflow (lb)	TCE Outflow (lb)	Total TCE in System (lb)
1 - 4	(Same as for Base Case)			
5	1988	0	4,929	12,141
6	1993	0	3,554	8,587
7	1998	0	2,587	6,000
8	2003	0	1,734	4,266
9	2008	0	1,054	3,212
10	2013	0	623	2,589
11	2018	0	355	2,234
12	2023	0	217	2,017
13	2028	0	135	1,882
14	2033	0	99	1,783
Total	(1983 - 2033)	0	15,287	
Total	(1963 - 2033)		28,620	

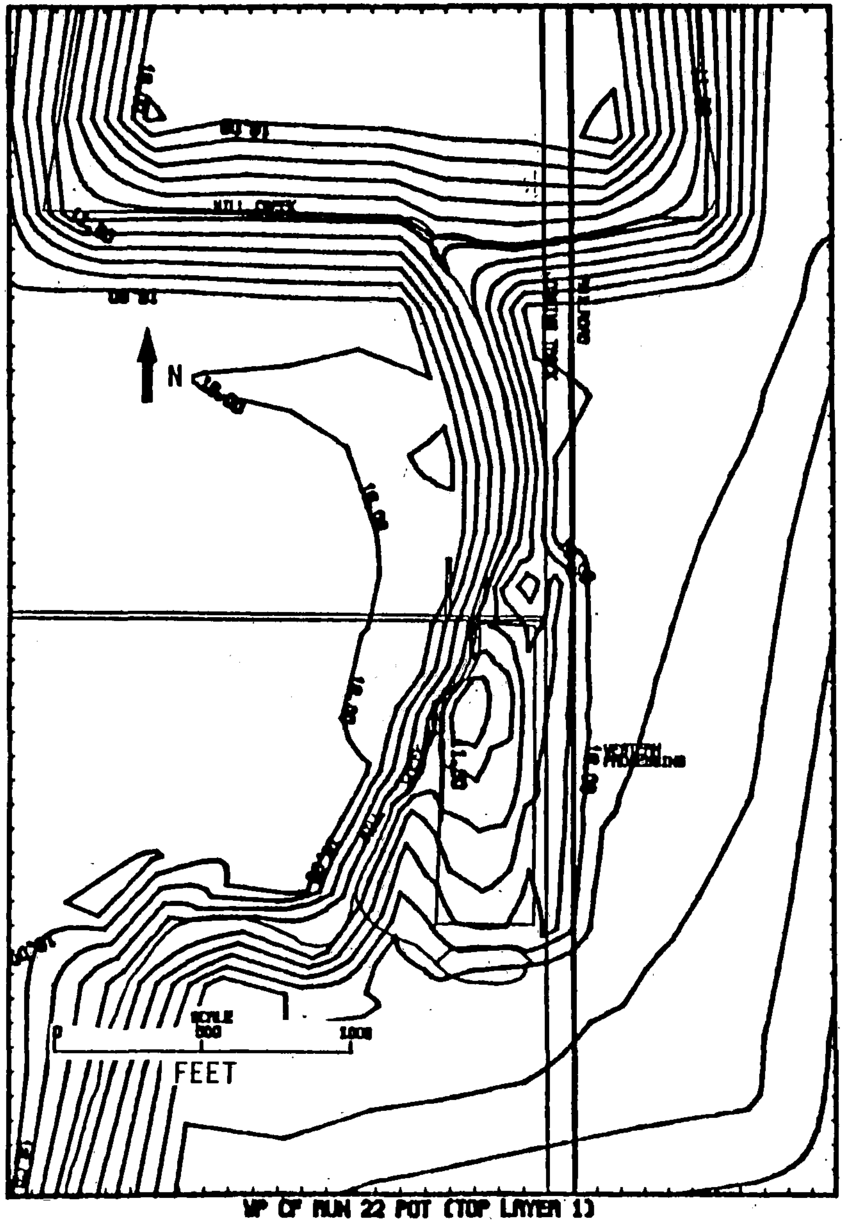


Figure 24. Predicted Top of Layer 1 Potential Surface for CH2M HILL Source Removal and Pump and Treat (100 gpm) Remedial Action

years. After 1983, 87% of the TCE exiting the system is removed by the pumping wells; the remaining 13% discharges to Mill Creek and the ditch.

TABLE 15. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE CH2M HILL SOURCE REMOVAL COMBINED WITH PUMP AND TREAT (100 GPM) REMEDIAL ACTION

Time Step	End Year	TCE Inflow (lb)	TCE Outflow (lb)		Total TCE in System (lb)
			Mill Creek	Pumping Wells	
1 - 4	(Same as Base Case)				
5	1988	0	1,880	13,679	1,512
6	1993	0	254	663	593
7	1998	0	59	534	0
8	2003	0	0	0	0
14	2033	0	0	0	0
Total		0	2,193	14,876	

Source Removal Combined with Pump and Treat (200 gpm)

This remedial action is similar to the previous action except that the 38 wells were pumped at a total rate of 200 gpm (758 l/min) instead of 100 gpm (379 l/min).

The potential surface for the top of Layer 1 for this case is shown in Figure 25. The average drawdown over the site due to pumping was about 8.5 ft (2.6 m).

The total mass of TCE in the flow system, and the total mass discharging to Mill Creek and the pumping wells at 5-year intervals are shown in Table 16. The model results show that all the TCE is removed from the system in the first 5 years. After 1983, 97% of the TCE exiting the system is removed by the pumping wells; the remaining 3% discharges to Mill Creek and the ditch.

Cap Combined with Pump and Treat (100 gpm)

The capping action assumes that the site is covered with a low permeability material in order to eliminate the infiltration of water through the unsaturated zone and the resulting leaching of TCE into the saturated

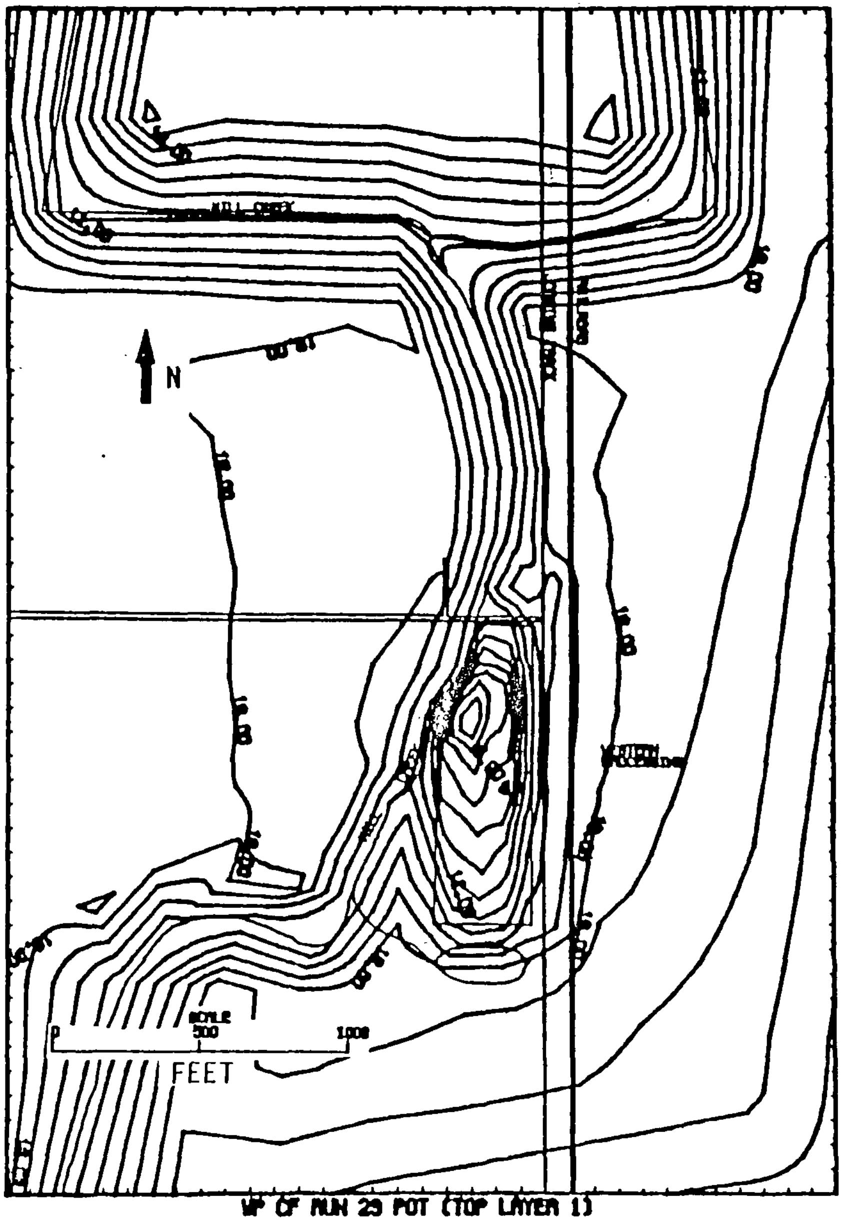


Figure 25. Predicted Top of Layer 1 Potential Surface for CH2M HILL Source Removal and Pump and Treat (200 gpm) Remedial Action

flow system. The capping action would be followed by the installation of wells to pump and treat contaminated groundwater.

TABLE 16. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE CH2M HILL SOURCE REMOVAL COMBINED WITH PUMP AND TREAT (200 GPM) REMEDIAL ACTION

Time Step	End Year	TCE Inflow (lb)	TCE Outflow (lb) Mill Creek	TCE Outflow (lb) Pumping Wells	Total TCE in System (lb)
1 - 4	(Same as Base Case)				
5	1988	0	545	16,526	0
6	1993	0	0	0	0
14	2033	0	0	0	0
Total		0	545	16,526	

The cap was simulated in the model by reducing the recharge rate over the site to 0.8 in./yr (2 cm/yr) or one-tenth the estimated annual average. The pump and treat action was simulated as discussed in the previous case where the pumping rate was 100 gpm (379 l/min).

The potential surface for the top of Layer 1 for this case is shown in Figure 26. The average drawdown over the site due to pumping was about 4.5 ft (1.4 m).

The total mass of TCE in the flow system, the mass entering from the unsaturated zone, and the mass discharging to Mill Creek and the pumping wells at 5-year intervals are shown in Table 17. The model results show that 92% of the TCE is removed from the system in the first 5 years, and that all of the TCE is removed in 15 years. After 1983, 88% of the TCE exiting the system is removed by the pumping wells; the remaining 12% discharges to Mill Creek and the ditch.

Cap Combined with Pump and Treat (200 gpm)

This remedial action is similar to the previous action except that the 38 wells were pumped at a total rate of 200 gpm (758 l/min) instead of 100 gpm (379 l/min).

The potential surface for the top of Layer 1 for this case is shown in Figure 27. The average drawdown over the site due to pumping was about 9 ft (2.7 m).

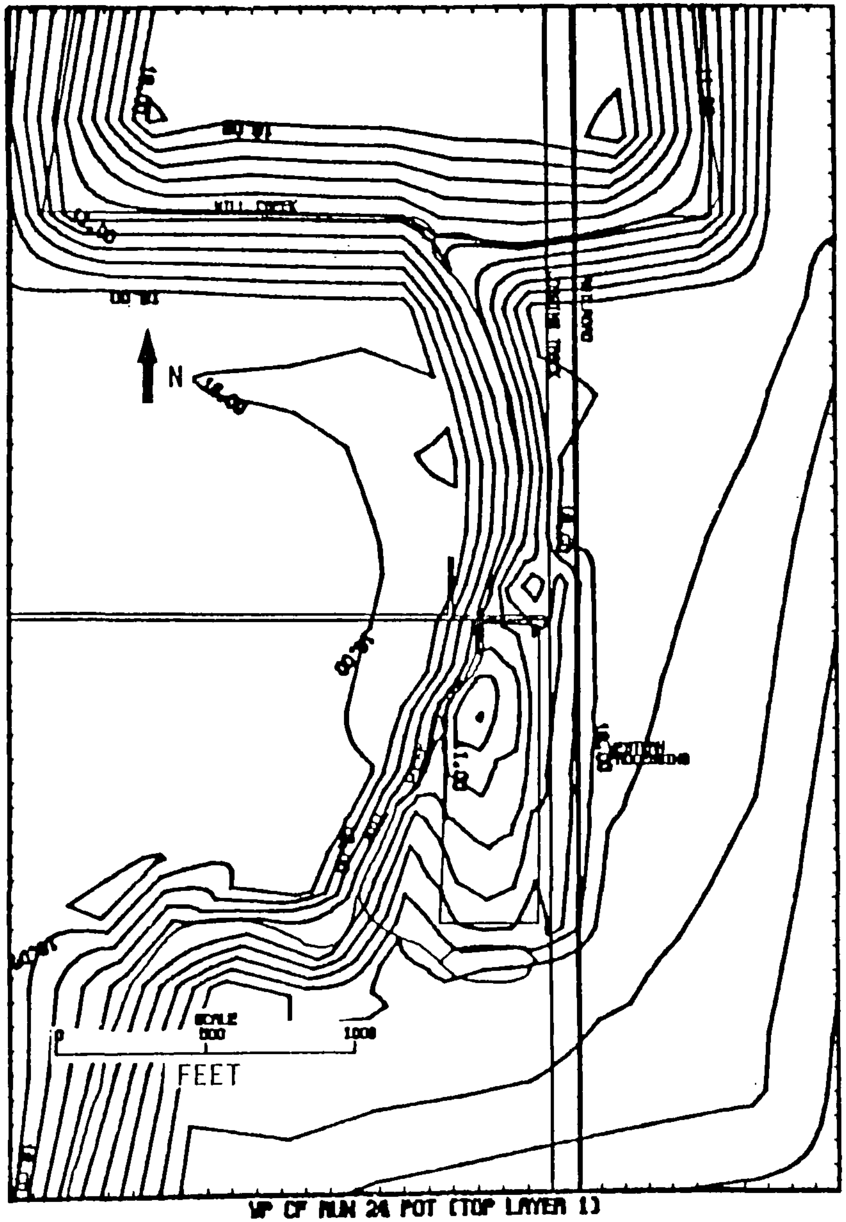


Figure 26. Model-Predicted Top of Layer 1 Potential Surface for the CH2M HILL Cap and Pump and Treat (100 gpm) Remedial Action

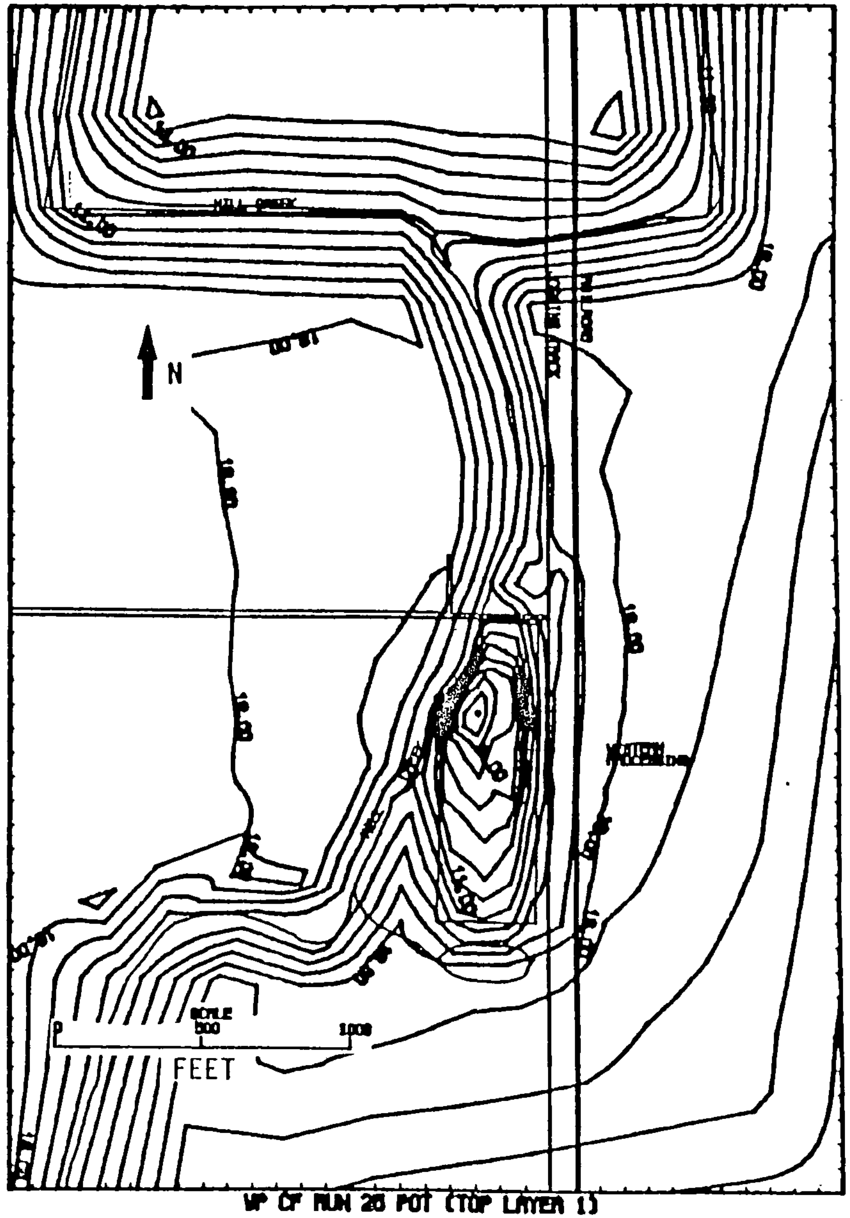


Figure 27. Model-Predicted Top of Layer 1 Potential Surface for the CH2M HILL Cap and Pump and Treat (200 gpm) Remedial Action

TABLE 17. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE CH2M HILL CAP COMBINED WITH PUMP AND TREAT (100 GPM) REMEDIAL ACTION

Time Step	End Year	TCE Inflow (lb)	TCE Outflow (lb) Mill Creek	TCE Outflow (lb) Pumping Wells	Total TCE in System (lb)
1 - 4	(Same as Base Case)				
5	1988	98	1,822	14,040	1,307
6	1993	25	220	528	584
7	1998	7	47	530	0
8	2003	0	0	0	0
14	2033	0	0	0	0
Total		130	2,089	15,105	

The total mass of TCE in the flow system, the mass entering from the unsaturated zone, the mass discharging to Mill Creek, and the mass removed by pumping wells at 5-year intervals are shown in Table 18. The model results show that virtually all of the TCE is removed from the system in the first 5 years. The only TCE remaining in the system after 5 years is the small amount that enters from the unsaturated zone. After 1983, 97% of the TCE exiting the system is removed by the pumping wells; the remaining 3% discharges to Mill Creek and the ditch.

TABLE 18. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE CH2M HILL CAP COMBINED WITH PUMP AND TREAT (200 GPM) REMEDIAL ACTION

Time Step	End Year	TCE Inflow (lb)	TCE Outflow (lb) Mill Creek	TCE Outflow (lb) Pumping Wells	Total TCE in System (lb)
1 - 4	(Same as Base Case)				
5	1988	97	519	16,649	0
6	1993	25	0	25	0
7	1998	0	0	0	0
14	2033	0	0	0	0
Total		0	519	16,674	0

PRPS PROPOSED REMEDIAL ACTION

The PRPs proposed remedial action is discussed in detail in the report by Landau Associates and Dames and Moore (1984). In summary, they proposed a combination of source removal, a slurry wall around the site, and pumping and treatment. In order to more thoroughly analyze their proposal in the model, a series of six model runs were performed.

The first model run was a no-action simulation to provide a benchmark against which the remedial action runs could be compared. The second model run simulated a slurry wall combined with source removal. The third and fourth model runs simulated the combination of slurry wall, source removal, and pump and treat, at total pumping rates of 100 and 200 gpm (379 and 758 l/min). To evaluate the effectiveness of the slurry wall, the fifth and sixth model runs were similar to the third and fourth runs except that the slurry wall was removed.

No Action (Extension of the Base Case)

The PRPs no-action simulation is basically the same as the no-action case for the CH2M HILL simulations, except that the finite element grid was modified for the PRPs simulations to contain elements which represent the slurry wall. In the no-action case the slurry wall elements were assigned the same permeability as surrounding elements. For cases involving the slurry wall, these elements were assigned a permeability of 2.8×10^{-4} ft/day (10^{-7} cm/sec). The purpose of this simulation was to verify that the same model solution was achieved for the finite element grid with the normal permeability slurry wall elements as for the grid without the slurry wall elements.

The potential surfaces for the PRPs no-action case are the same as for the original base case (Figures 8 to 12). The TCE concentration contours are nearly identical to those for the CH2M HILL no-action case (Figures 21 through 23).

The total mass of TCE in the flow system, the mass entering the system, and the mass discharging to Mill Creek and the ditch over 5-year intervals are shown in Table 19. The numbers in this table are different than those in Table 13 (CH2M HILL no-action case) because the areas of the Reaction Pond III and Well 21 sources are slightly smaller (the slurry wall elements

TABLE 19. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE PRPS NO-ACTION SIMULATION

Time Step	End Year	TCE Inflow (lb)	TCE Outflow (lb)	Total TCE in System (lb)
1*	1968	7,034	919	6,115
2*	1973	7,034	2,612	10,537
3*	1978	7,034	3,815	13,756
4*	1983	7,034	4,757	16,033
5	1988	975	4,619	12,389
6	1993	244	3,497	9.136
7	1998	61	2,688	6,509
8	2003	15	1,909	4,615
9	2008	0	1,231	3,384
10	2013	0	788	2,596
11	2018	0	505	2,091
12	2023	0	358	1,733
13	2028	0	270	1,463
14	2033	0	223	1,240
Total		29.431	28,191	

*Base case.

removed a 3 ft (1 m) strip along western edge). After the first four time steps, when sources around Reaction Pond III and Well 21 are no longer active, the amount of TCE entering the system from Reaction Pond I is identical to the base case, thus, it appears that adding the extra elements does not change the model results significantly. As a result, all PRPs cases were simulated with the slightly reduced area of the source around Reaction Pond III and Well 21.

The results of the PRPs no-action run served as a benchmark against which the PRPs remedial action simulations could be compared. The results showed that 28,136 lb (12,730 Kg) of TCE entered the groundwater flow system between 1963 and 1983, and that an additional 1,295 lb (586 Kg) leached in from the unsaturated zone over the next 20 years. By 1983, 12,103 lb (5,476 Kg) were discharged to either Mill Creek (97%) or the ditch (3%), and 16,033 lb (7,254 Kg) remained in the system.

Source Removal and Slurry Wall

This model run simulated a combined source removal and slurry wall remedial action. The source removal action assumes that the unsaturated material contaminated with TCE is excavated and removed from the site. This action was simulated in the model by eliminating all input of TCE to the groundwater flow system after 1983.

The slurry wall was simulated in the model as a series of 3 ft (1 m) wide elements around the perimeter of the site (Figure 4). The slurry wall elements were assigned a permeability of 2.8 x 10^{-4} ft/day (10^{-7} cm/sec) and the wall extended to a depth of 50 ft below the surface (40 ft below the water table). The intent of the wall was to contain the contamination on site, reduce the lateral flow to the wells, and increase upward vertical flow.

The potential surfaces for this case are essentially the same as those for the base case (Figure 8 - 12). The potential on site averages about 0.6 ft (0.2 m) higher than the base case potential due to the impact of the slurry wall.

The distribution of TCE in the flow system at 5-year intervals is shown in Table 20. Comparing these results to the results for the no-action case

TABLE 20. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE PRPS SOURCE REMOVAL WITH A SLURRY WALL REMEDIAL ACTION

Time Step	End Year	TCE Inflow (lb)	TCE Outflow (lb)	Total TCE in System (lb)
1 - 4	(Same as for Base Case)			
5	1988	0	3,645	12,388
6	1993	0	2,513	9,875
7	1998	0	2,232	7,643
8	2003	0	1,712	5,931
9	2008	0	1,265	4,666
10	2013	0	864	3,802
11	2018	0	608	3,194
12	2023	0	457	2,737
13	2028	0	368	2,369
14	2033	0	309	2,060
Total		0	13,973	

shows that the slurry wall prevents the TCE from migrating off site, thereby increasing the mass of TCE on site and reducing the TCE loading to Mill Creek. All TCE exiting the system either goes to Mill Creek (97%) or the ditch (3%).

Source Removal, Slurry Wall, Pump and Treat (100 gpm)

This model run simulated the remedial action proposed by the PRPs. It consisted of a combination of source removal, pump and treat at 100 gpm (379 l/min), and a slurry wall around the perimeter of the site.

The source removal and slurry wall actions were simulated in the same manner as discussed in the previous case. As stated earlier, for this remedial action involving pumping from shallow wells, the purpose of the slurry wall was not only to contain the contamination, but to reduce the lateral flow of water from off site to the wells, and induce upward flow through the highly contaminated near-surface materials on site. Pump and treat was simulated in the same manner as in the CH2M HILL cases. Water was withdrawn from a network of 38 wells evenly distributed over the site. The wells were drilled to 30 ft (9 m) below the water table and the total withdrawal rate from all wells was 100 gpm (379 l/min). The major difference between the CH2M HILL and PRPs cases is that in the PRPs cases, pumping was simulated for the first 5 years of the 50-year simulation period instead of for the first 30 years as in the CH2M HILL simulations.

The potential surface for the top of Layer 1 for this case is shown in Figure 28. The average drawdown over the site due to pumping is about 6 ft (1.8 m).

The distribution of TCE in the flow system for this case is shown in Table 21. The results show that 84% of the TCE presently in the flow system (1983) will be removed after 5 years of pumping. All of the TCE is removed from the system in 15 years (after the first 5 years it discharges to Mill Creek because pumping is stopped). Of the TCE exiting the system in the first 5 years, 84% is withdrawn by the pumping wells, and the remaining 16% goes to Mill Creek or the ditch.

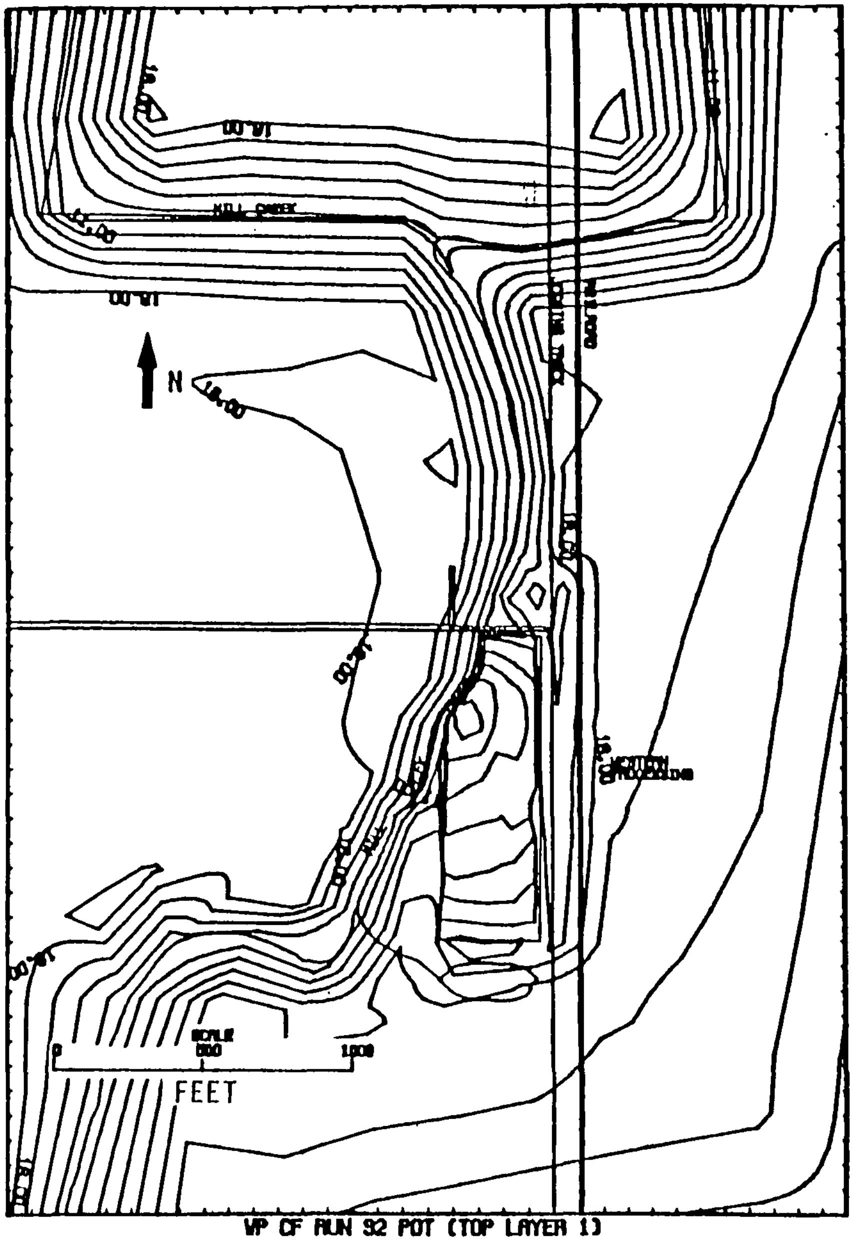


Figure 28. Model-Predicted Top of Layer 1 Potential Surface for the PRPs Slurry Wall and Pump and Treat (100 gpm) Remedial Action

TABLE 21. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE PRPS SOURCE REMOVAL, SLURRY WALL, AND PUMP AND TREAT (100 GPM) REMEDIAL ACTION

Time Step	End Year	TCE Inflow (lb)	TCE Outflow (lb) Mill Creek	Pumping Wells	Total TCE in System (lb)
1 - 4	(Same as Base Case)				
5	1988	0	2,153	11,303	2,577
6	1993	0	1,508	0	1,069
7	1998	0	1,069	0	0
8	2003	0	0	0	0
14	2033	0	0	0	0
Total		0	4,730	11,303	

Source Removal, Slurry Wall, Pump and Treat (200 gpm)

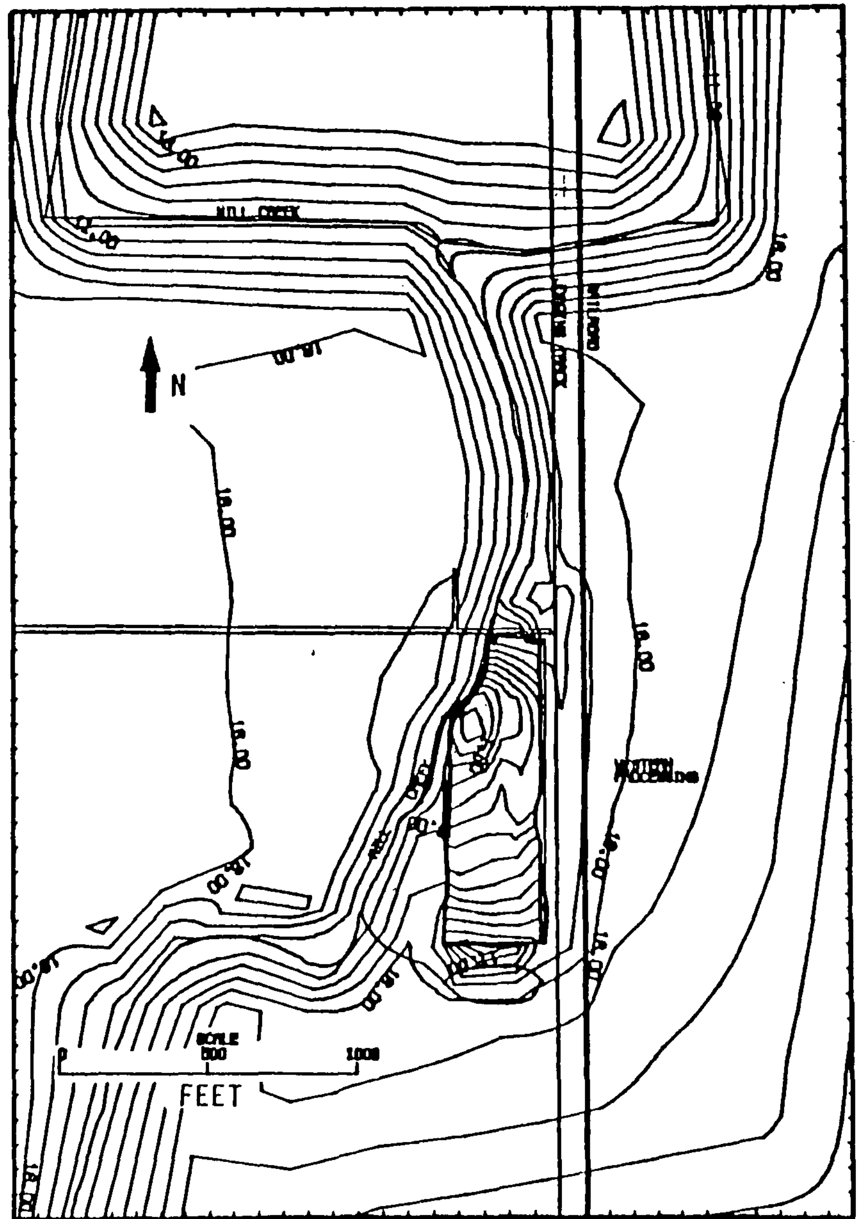
This remedial action is similar to the previous action except that the 38 wells were pumped at a total rate of 200 gpm (758 l/min) instead of 100 gpm (379 l/min). The 200 gpm pumping rate is twice the rate proposed by the PRPs.

The potential surface for the top of Layer 1 for this case is shown in Figure 29. The average drawdown over the site due to pumping is about 12 ft (3.6 m).

The distribution of TCE in the flow system for this case is shown in Table 22. The results show that all of the TCE exits the flow system in the first 5 years. Of the total leaving the system, 97% is withdrawn by the pumping wells and 3% discharges to the creek or ditch.

Source Removal, Pump and Treat (100 gpm), No Slurry Wall

In order to evaluate the benefit of a slurry wall, this case simulated source removal and pump and treat (total of 100 gpm) without the slurry wall. All parameters were identical to the previous case which simulated the PRPs proposed remedial action, except that this case did not include the slurry wall.



VP CF RUN 93 POT (TOP LAYER 1)

Figure 29. Model-Predicted Top of Layer 1 Potential Surface for the PRPs Source Removal, Pump and Treat (200 gpm), and Slurry Wall

TABLE 22. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE PRPS SOURCE REMOVAL, SLURRY WALL, AND PUMP AND TREAT (200 GPM) REMEDIAL ACTION

Time Step	End Year	TCE Inflow (lb)	TCE Outflow (lb) Mill Creek	TCE Outflow (lb) Pumping Wells	Total TCE in System (lb)
1 - 4	(Same as Base Case)				
5	1988	0	481	15,552	0
6	1993	0	0	0	0
14	2033	0	0	0	0
Total		0	481	15,552	

The potential surface for the top of Layer 1 for this case is shown in Figure 30. The average drawdown over the site due to pumping was about 4 ft (1.2 m). The drawdown was greater in the case with the slurry wall (6 ft) because the wall cut off much of the lateral flow.

The distribution of TCE in the flow system for this case is shown in Table 23. The results show that 92% of the TCE in the system in 1983 will be removed after 5 years of pumping and all the TCE exits the system after 20 years (after the first 5 years it goes to Mill Creek because the pumps are turned off). Of the TCE exiting the system in the first 5 years, 89% is withdrawn by the pumping wells and the remaining 11% discharged to Mill Creek or the ditch.

TABLE 23. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE PRPS SOURCE REMOVAL AND PUMP AND TREAT (100 GPM) REMEDIAL ACTION (NO SLURRY WALL)

Time Step	End Year	TCE Inflow (lb)	TCE Outflow (lb) Mill Creek	TCE Outflow (lb) Pumping Wells	Total TCE in System (lb)
1 - 4	(Same as Base Case)				
5	1988	0	1,623	13,134	1,276
6	1993	0	431	0	845
7	1998	0	569	0	276
8	2003	0	276	0	0
14	2033	0	0	0	0
Total		0	2,899	13,134	

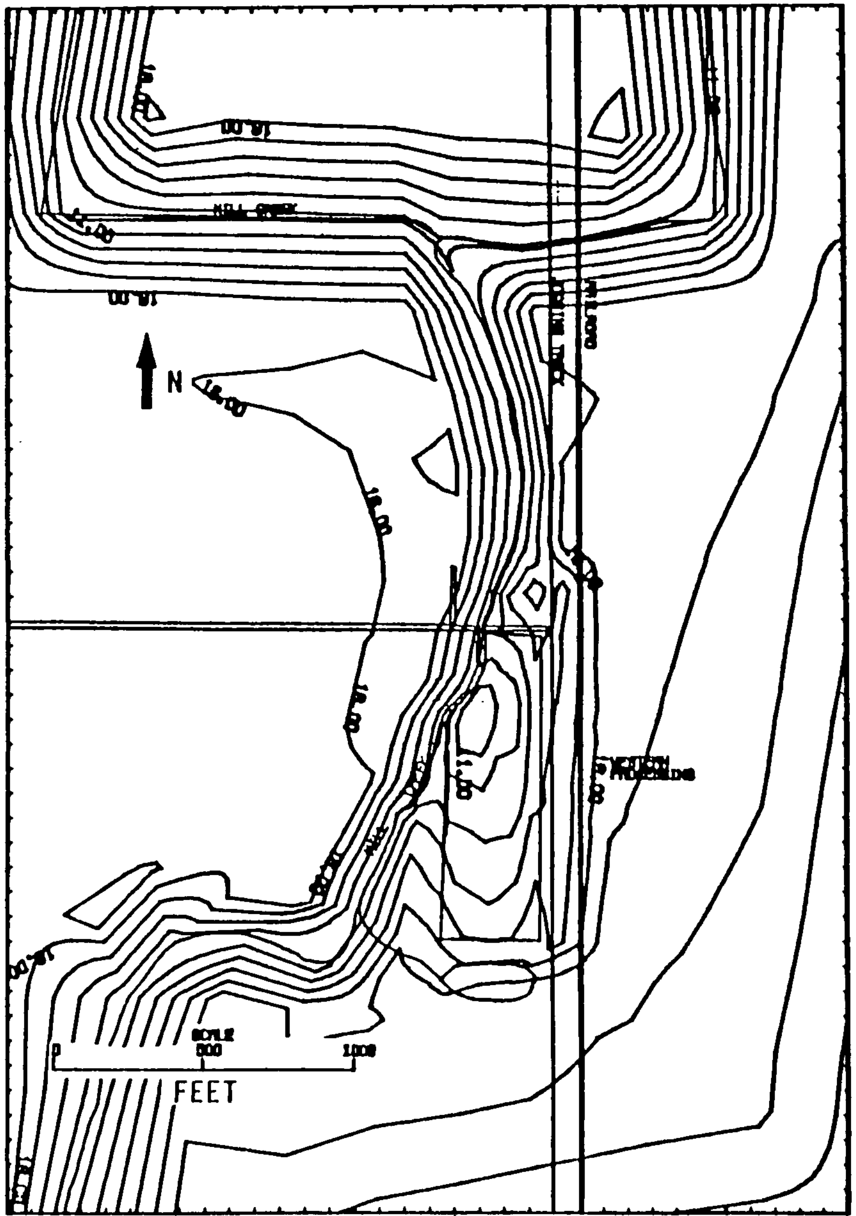


Figure 30. Predicted Top of Layer 1 Potential Surface for the PRPs Pump and Treat (100 gpm) Remedial Action with no Slurry Wall

Source Removal, Pump and Treat (200 gpm), No Slurry Wall

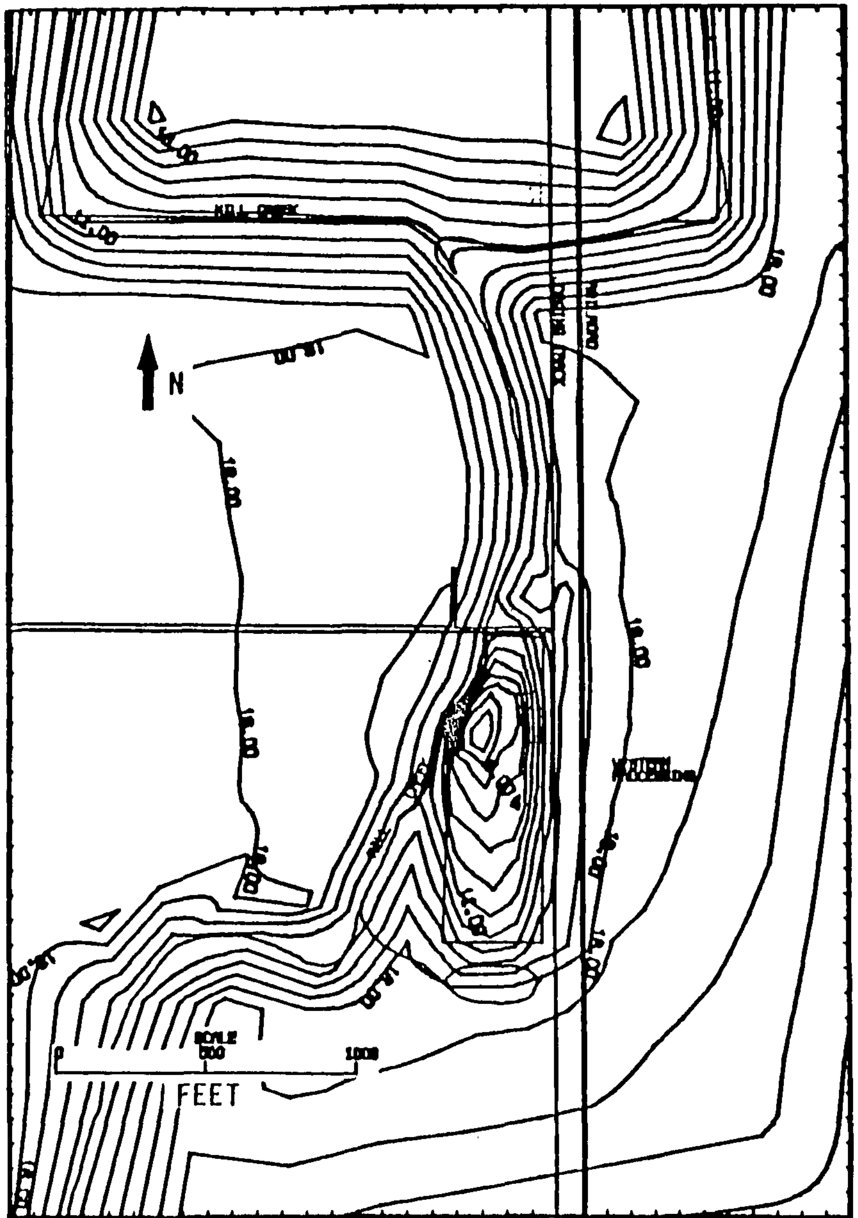
A simulation was made with source removal and pump and treat (total of 200 gpm) without the slurry wall. All model parameters were identical to the PRPs proposed remedial action with the 200 gpm pumping rate except that the slurry wall was eliminated.

The potential surface for the top of Layer 1 for this case is shown in Figure 31. The average drawdown over the site due to pumping was about 8.5 ft (2.4 m). The drawdown was greater in the case with the slurry wall (12 ft) because the wall cut off much of the lateral flow.

The distribution of TCE in the flow system for this case is shown in Table 24. The results show that all the TCE exits the flow system in the first 5 years. Of the total exiting the system, 97% is withdrawn by the pumping wells and 3% discharges to Mill Creek or the ditch.

TABLE 24. MODEL-PREDICTED DISTRIBUTION OF TCE FOR THE PRPS SOURCE REMOVAL AND PUMP AND TREAT (200 GPM) REMEDIAL ACTION (NO SLURRY WALL)

Time Step	End Year	TCE Inflow (lb)	TCE Outflow (lb) Mill Creek	Pumping Wells	Total TCE in System (lb)
1 - 4	(Same as Base Case)				
5	1988	0	481	15,552	0
6	1993	0	0	0	0
14	2033	0	0	0	0
Total		0	481	15,552	



WP CF RUN 95 POT (TOP LAYER 1)

Figure 31. Model-Predicted Top of Layer 1 Potential Surface for the PRPs Pump and Treat (200 gpm) Remedial Action with no Slurry Wall

SECTION 8

SUMMARY

A summary of the base case and remedial action simulation results is discussed in this section.

BASE CASE

TCE was introduced to the groundwater flow system in the model over a period of 20 years (1963 - 1983) at three source locations: 1) Reaction Pond I; 2) Reaction Pond III; and 3) around Well 21. Over this 20 year period the model predicted that 30,400 lb (13,789 Kg) of TCE was spilled at the site. Over the same period, about 13,300 lb (6,033 Kg) discharged to Mill Creek or the railroad drainage ditch, with 17,100 lb (7,756 Kg) remaining in the flow system in 1983. This number compares well with the estimated mass of TCE in the flow system of 18,000 lb (8,165 Kg) calculated independently by CH2M HILL (1985) and Landau Associates and Dames and Moore (1984) based on the 1982 through 1984 chemistry data for the site. Of the 30,400 lb (13,789 Kg) of TCE that was spilled at the site, the model indicated that 13%, 37%, and 50% originated in the area of Reaction Pond I, Reaction Pond III, and Well 21, respectively.

A summary of the results for both the CH2M HILL and PRPs remedial action simulations is shown in Table 1 (Section 2). A comparison of the total mass of TCE remaining in the groundwater flow system for the CH2M HILL and PRPs remedial action cases is shown in Figure 1a and 1b, respectively (Section 2).

For both the CH2M HILL and the PRPs simulations, the base and no-action case results in Figures 1a and 1b are essentially the same. The results would be identical except that the slurry wall elements in the PRPs cases reduced the size of the Reaction Pond III and Well 21 source areas in the model, thereby slightly reducing the mass loading of TCE at these areas.

The model results show that Mill Creek has been and will continue to be, if no remedial actions are taken, the primary discharge point for TCE migrating from the Western Processing Site. In the base case (1963 - 1983) and the no-action case (1983 - 2033), about 97% of the TCE exiting the system discharges to Mill Creek, and the remaining 3% discharges to the drainage ditch along the eastern boundary of the site. According to the model, no TCE enters the regional groundwater flow system which flows toward the Green River; all the TCE remains in the local flow system controlled by Mill Creek and the drainage ditch. By 1983, a little less than half (44%) of the TCE that was estimated to have entered the flow system during site operation had exited to Mill Creek and the ditch. For the no-action simulation, the model predicted that 89% and 96% of the total mass of TCE that entered the system discharged to Mill Creek or the ditch by the years 2008 and 2033 (25 and 50 years into the future), respectively.

REMEDIAL ACTIONS

Two sets of remedial action runs were simulated with the model: those based on the remedial actions proposed by CH2M HILL; and those based on the remedial actions proposed by the PRPs. The model runs based on the CH2M HILL proposed actions were:

1) no-action (extend the base case into the future);
2) source removal;
3) source removal and pump and treat (100 gpm);
4) source removal and pump and treat (200 gpm);
5) cap and pump and treat (100 gpm); and
6) cap and pump and treat (200 gpm).

The model runs based on the PRPs proposed actions were:

1) no-action;
2) source removal combined with a slurry wall;
3) source removal, slurry wall, and pump and treat (100 gpm);
4) source removal, slurry wall, and pump and treat (200 gpm);
5) source removal and pump and treat (100 gpm) (no slurry wall); and
6) source removal and pump and treat (200 gpm) (no slurry wall).

The no-action simulations consisted of running the base case (1963 - 1983) 50 years into the future in order to provide a benchmark against which remedial action cases could be compared.

The source removal action (excavation of contaminated unsaturated soils) alone is ineffective in cleaning up the TCE on site because apparently very little TCE remains in the unsaturated soils. According to the calculations shown in Appendix A, only about 1,300 lb (590 Kg) of TCE currently exists in the unsaturated zone on site. Of this total, 99% is present in the unsaturated soils in the area around Reaction Pond I. Most likely, the source removal action would be effective for constituents with high affinity for adsorption such as metals and other highly sorbed contaminants. Therefore, this action should not be construed to be universally ineffective at the Western Processing Site based on the predictions for TCE.

In the CH2M HILL cases, the source removal and capping actions combined with pumping and treatment achieved about the same results; the action involving source removal is slightly more effective in reducing the TCE mass loading to Mill Creek, but a slightly greater contaminant mass remains in the system than for the action involving capping. These results are similar because both actions essentially eliminate the leaching of TCE from the unsaturated zone to the saturated groundwater system. The cap eliminates only about 5 gpm (19 l/min) of recharge over the site, a small number compared to the 100 gpm and 200 gpm (379 and 758 l/min) pumping rates.

In the PRPs cases, the remedial actions without the slurry wall were more effective in reducing the total mass of TCE in the system and the mass of TCE exiting to Mill Creek and the ditch, than the cases with the slurry wall. The reason for this is that the slurry wall prevented the pumping wells from removing contamination which is outside the slurry wall. The slurry wall is effective in reducing the lateral flow of water from the creek to the puming wells, and thereby reducing the total quantity of water that requires treatment. Also, the slurry wall is effective in containing contamination once the pumping ceases. The slurry wall would be more effective if a cap were also installed over the site to reduce the amount of recharge. The cap would reduce the leaching and transport of contaminants through the system and under the wall. Even without the cap, however, the rate of migration of contamination through the site and under the wall could be low enough that the concentrations would be diluted to acceptable levels in the groundwater flow system.

In all cases involving pumping, withdrawal of water at the 200 gpm (758 l/min) rate removed all the TCE from the system in the first 5 years. About 97% of the TCE was removed by the pumping wells with the remainder discharging to Mill Creek (and a trace to the drainage ditch).

In the CH2M HILL cases and the PRPs case with the slurry wall, pumping at the 100 gpm (379 l/min) rate removed all the TCE in the first 15 years. In all three cases, most of the TCE (about 90%) exits the sytem in the first 5 years. Over the 15-year period, between 85% and 90% of the TCE is removed by the pumping wells for the CH2M HILL cases. In the CH2M HILL cases, pumping was simulated for the first 30 years (1983 - 2013), whereas in the PRPs cases, pumping was simulated for just the first 5 years (1983 - 1988). Therefore, in the PRPs cases, all TCE exiting the system after the first 5 years discharges to Mill Creek or the ditch.

In the PRPs case of source removal and pump and treat at 100 gpm without the slurry wall, 20 years were required for all the TCE to exit the system. Ninty-two percent of the TCE exited the system during the first 5 years of pumping. Of this amount, 89% was removed by the pumping wells, and the remainder discharged to Mill Creek and the ditch. After the pumping ceased an additional 15 years was required for the TCE to discharge to Mill Creek or the ditch.

The drawdown over the site for all cases involving pumping ranged between 4 and 12 ft (1.2 and 4.6 m). The 100 gpm (379 l/min) pumping rate resulted in average drawdowns between 4 and 6 ft (1.2 and 1.8 m) whereas the 200 gpm (758 l/min) pumping rate resulted in average drawdowns between 8 and 12 ft (2.4 and 3.7 m). For the same pumping rate, the cases with the slurry wall had about 2 to 3 ft (0.6 to 0.9 m) more drawdown because the wall eliminated lateral flow to the wells.

In summary, to a large degree the CH2M HILL and PRPs remedial action cases performed about equally. As expected, the modeling results indicated that the 200 gpm (758 l/min) pumping rate performed better than the 100 gpm (379 l/min) rate. These data and other differences which are discernable in the model results should be considered in the selection of the remedial action alternative to be implemented at the site.

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APPENDIX A

CALCULATION OF LEACH DURATION AND AMOUNT FROM SOURCE AREAS

Three sources of TCE have been identified at the Western Processing Site, based on the concentration levels measured in the soil and water. These three sources are: 1) Reaction Pond I; 2) Reaction Pond III; and 3) around Well 21. Calculations were made to estimate the mass of TCE present in the unsaturated zone (both in soil and water) of these three locations based on 1982 soil concentration measurements (EPA, 1983 and 1984). These mass estimates were then used to estimate the time required for TCE to completely leach the unsaturated zone into the saturated zone. Time of leach calculations were based on the average annual recharge at the site (8 in./yr). The results of these calculations were used to determine the number of years past 1982 to keep the sources active in the model, and to estimate the source strength for each time step simulated.

SOURCE AREA DATA

The data used to estimate the mass of TCE in the unsaturated zone of each source area are summarized below.

Reaction Pond I

The total volume of contaminated unsaturated soil at Reaction Pond I was estimated to be 46,250 ft^3. This number is based on a surface area of 9,250 ft^2 and an average depth of unsaturated contaminated soil of 5 ft. The surface area is the actual area associated with Reaction Pond I. The average depth of contaminated soil was estimated from the soil sampling depths and concentrations reported in Table A-1. The TCE concentration in the soil was estimated to be 600,000 ppb based on the measured soil concentrations from the borings at Wells 15 and 17 (Table A-1). In order to represent a worst case, the concentration was assumed to be the maximum observed soil concentration and to be uniform over the area of the disposal site.

Table A-1. TCE Soil Concentrations Near Reaction Pond I

Depth (ft)	Soil Concentration (ppb)	
	Well 15	Well 17
3	U	U
6	580,000	558,000
9	180,000	350,000

U = Not Detected

Reaction Pond III

The total volume of contaminated, unsaturated soil at Reaction Pond III was estimated to be 35,650 ft^3. This number is based on a surface area of 7,125 ft^2 and an average depth of contaminated soil of 5 ft. The surface area is the actual area of Reaction Pond III. The average depth of contaminated soil was estimated from the soil sampling depths and concentrations reported in Table A-2. The TCE concentration in the soil was estimated to be 700 ppb based on the measured soil concentrations from Well 20 (Table A-2). In order to represent a worst case, the concentration was assumed to be the maximum observed soil concentration and was assumed to be uniform over the area of the disposal site.

Table A-2. TCE Soil Concentrations Near Reaction Pond III

Depth (ft)	Soil Concentration (ppb)
	Well 20
3	U
6	M
9	676
12	544

U = Not Detected

M = Present but below minimum quantifiable limit.

Area Around Well 21

The total volume of contaminated unsaturated soil in the area around Well 21 was difficult to estimate because the area of disposal is not known. Therefore, the volume was assumed to be the same as that of Reaction Pond III, 35,650 ft^3. The TCE concentration in the soil was estimated to be 1,600 ppb based on the measured soil concentration from Well 21 (Table A-3).

Table A-3. TCE Soil Concentrations in Well 21

	Soil Concentration (ppb)
Depth (ft)	Well 21
3	U
6	U
9	116
12	1,520

U = Not Detected

CALCULATION OF SOURCE AREA MASS

The calculations of mass in the unsaturated zone for each of the three source locations are presented below.

For all source areas, the actual and effective porosities of the unsaturated material were assumed to be 0.25 and 0.15, respectively. The distribution coefficient (Kd) of TCE in the unsaturated soils was set at 0.2 at all source locations.

The equation used to calculate the mass of TCE at each source location is:

$$Mass_{TCE} = \{\text{mass in soil}\} + \{\text{mass in water}\}$$
$$= (C_s)(Vol_s)(\gamma_s) + (\Theta)(C_w)(Vol_s)(\gamma_w) \qquad \text{(A-1)}$$

where

$Mass_{TCE}$ = total mass of TCE in the soil (lb)

Θ_A = actual porosity

Θ = moisture content

C_s = TCE concentration (ppb) in the soil

Vol_s = total volume of unsaturated soil (ft^3)

γ_s = density of the soil (lb/ft^3)

C_w = TCE concentration (ppb) in the water $\{C_w = \frac{1}{Kd} (C_s)\}$

γ_w = density of the water (lb/ft^3)

Kd = distribution coefficient

The density of the soil was calculated as:

$$\gamma_s = (1 - \Theta_A)(\gamma) = 121.5 \text{ lb/ft}^3$$

where:

Θ_A = actual porosity (0.25)

γ = dry density of sand (162 lb/ft^3)

The TCE soil concentrations were based on measured soil concentrations in the unsaturated zone at wells around the source areas. The TCE water concentrations were estimated to be five times greater than the soil concentrations based on a distribution coefficient (Kd) of 0.2. The ppb notation is equivalent to lb per 10^9 lb in the total mass calculation.

Reaction Pond I

Based on the data in Table A-4, the total mass of TCE in the unsaturated zone at Reaction Pond I was calculated to be 4,670 lb. The total mass in the soil and water was calculated to be 3,370 lb and 1,300 lb, respectively.

Table A-4. Summary of Data Used to Make Total Mass Calculations at all Three Source Locations

	Reaction Pond I	Reaction Pond III	Well 21
Θ	0.15	0.15	0.15
Θ_A	0.25	0.25	0.25
C_s (ppb)	600,000	700	1,600
C_w (ppb)	3,000,000	3,500	8,000
Vol_s (ft^3)	46,250	35,650	35,650
γ_s (lb/ft^3)	121.5	121.5	121.5
γ_w (lb/ft^3)	62.4	62.4	62.4
Kd	0.2	0.2	0.2

Reaction Pond III

Based on the data in Table A-4, the total mass of TCE in the unsaturated zone at Reaction Pond III was calculated to be 4.2 lb. The total mass of TCE in the soil and water were calculated to be 3.0 lb and 1.2 lb, respectively.

Around Well 21

Based on the data in Table A-4, the total mass of TCE in the unsaturated zone around Well 21 was calculated to be 9.6 lb. The total mass in the soil and water were calculated to be 6.9 lb and 2.7 lb, respectively.

The estimated total mass of TCE present in the unsaturated zone (based on October, 1982, soil analyses) at the three suspected source areas is summarized in Table A-5.

Table A-5. Summary of Estimated Total Mass of TCE Present at the Three Suspected Source Areas

	Mass of TCE (lb)		
	In Soil	In Water	Total
Reaction Pond I	3,370	1,300	4,670
Reaction Pond III	3.0	1.2	4.2
Around Well 21	6.9	2.7	9.6

DURATION AND AMOUNT OF LEACHING FROM SOURCE LOCATIONS

The preceding calculations show that Reaction Pond I is the only source location which contains a significant quantity of TCE in the unsaturated zone. Calculations of the time required for TCE to leach out of the unsaturated zone (duration), and of the amount that would leach out each year, were made for Reaction Pond I. This information was used in the modeling to determine the length of time into the future that Reaction Pond I would remain active, and the quantity of TCE that would leach from the unsaturated to the saturated zone at each time step.

Reaction Pond I

The calculations were based on the concentration of TCE in the water of the unsaturated zone and the rate of water movement through the unsaturated zone from annual recharge. Equation A-1 can be used to calculate the TCE concentration in the water (C_w) based on the total mass of TCE remaining in the system at any given point in time. For convenience, the equation can be rewritten as follows:

$$C_w = \frac{Mass_{TCE}}{Vol_s \ (Kd \ \gamma_s + \theta \ \gamma_w)} \qquad \text{(A-2)}$$

The Kd in equation A-2 is equivalent to C_s/C_w.

The volume of water (Vol_w) moving through the unsaturated zone from the average annual recharge was calculated as follows:

$$Vol_w = Rhg \times A = 6{,}167 \ ft^3/yr$$

where

Rhg = average annual recharge (0.67 ft/yr)

A = area of Reaction Pond I (9,250 ft^2)

This number was used to calculate the mass of water ($Mass_w$) passing through the unsaturated system, as follows:

$Mass_w = Vol_w \times \gamma_w = 384,800$ lb/yr γ

The initial mass of TCE in the system was 4,670 lb. For each year a mass of TCE removed from the system was calculated as C_w times $Mass_w$. A new mass of TCE in the system was calculated as the previous mass minus the mass removed, and the procedure was repeated. This iterative process continued until virtually all of the TCE was leached from the system. The results of this calculation are shown in Table A-6.

Table A-6. Time and Amount of TCE Leaching from the Unsaturated Zone at Reaction Pond I

	Mass TCE (lb)			Mass TCE (lb)	
Year	Remaining	Total Removed	Year	Remaining	Total Removed
1	4,670	1,154	11	273	4,464
2	3,516	2,023	12	206	4,515
3	2,647	2,678	13	155	4,554
4	1,992	3,178	14	116	4,582
5	1,500	3,541	15	88	4,604
6	1,129	3,820	16	66	4,620
7	850	4,030	17	50	4,632
8	640	4,188	18	38	4,641
9	482	4,307	19	29	4,648
10	363	4,397	20	22	4,653

Table A-6 shows that virtually all of the TCE in the unsaturated zone above Reaction Pond I is leached into the saturated zone in 20 yr. Over each 5-year period (the time step used in the model) about 75% of the mass of TCE remaining is flushed from the system. Based on these calculations, the Reaction Pond I source was allowed to leach for 20 years into the future in the model, and the source strength was reduced by 75% at every time step.

Reaction Pond III and Area Around Well 21

The total mass of TCE in the unsaturated zone above Reaction Pond III and in the area around Well 21 was so small that it was not necessary to make calculations of the leach duration and amount. As a result, these sources were allowed to leach up to the present, and then turned off for all model predictions into the future.

APPENDIX B

RECHARGE CALCULATIONS

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

Recharge = Precipitation - Actual Evaporation - Runoff (B-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 corresponds to curve number 85 if normally wet antecedent moisture conditions prevail, as might be expected 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 B-1.

TABLE B-1. RUNOFF PROGRAM RESULTS

Storm Separation Interval (days)	Runoff (in./yr)			
	1982		1983	
	CN 70	CN 85	CN 70	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

Using equation B-1, storm separation intervals of 0, 1, 2, and 3 days, and averaging the runoff over two years yields estimated recharges of about 5 in./yr (13 cm/yr) and 12 in./yr (30 cm/yr) for runoff curve numbers 70 and 85, respectively. The curve number that applies to the area around Kent is probably between 70 and 85. Therefore, the actual recharge was estimated to be about 8 in./yr (20 cm/yr).

In the final calibrated model a recharge value of 8 in./yr (20 cm/yr) was applied uniformly over the local model region except for paved areas on the Western Processing Site (Elements 128, 129, 130, 143, 144, 145, 146, 152, 153, 154, 163, 164, and 175) where the recharge was set to 0 in./yr.

APPENDIX C

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. This phenomenon is often treated in a groundwater model by holding the groundwater elevation at the level of the surface water. 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 C-1 and C-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 C-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	277.0	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
286	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 C-2. Stream Boundary Option Data Used to Simulate Flux to the Ditch

NODE NUMBER	CREEK ELEVATION	CREEK LENGTH	CREEK WIDTH	CREEK BOTTOM ELEVATION	CREEK BOTTOM THICKNESS	CREEK BOTTOM PERMEABILITY	MIN CREEK DEPTH
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	62.0	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 a constant flux or held potential at the boundary, the leakance option allows the potential and flux to be varied depending on the conditions which exist within the study area.

The data required by the model to make this calculation arethe 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, including both surface nodes and nodes at depth. The model calculates a boundary flux at each node using Darcy's Law, which is then used to calculate the potential at the boundary.

A map depicting the regional potentials used to calculate the groundwater potential at certain distances from the boundaries is shown in Figure C-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 (3.0 m) AMSL;
2. east of benchmark 22 (west of site) - 8.8 ft (2.7 m) AMSL; and
3. Tukwilla Gauge (north of site) - 7.9 ft (2.4 m) AMSL.

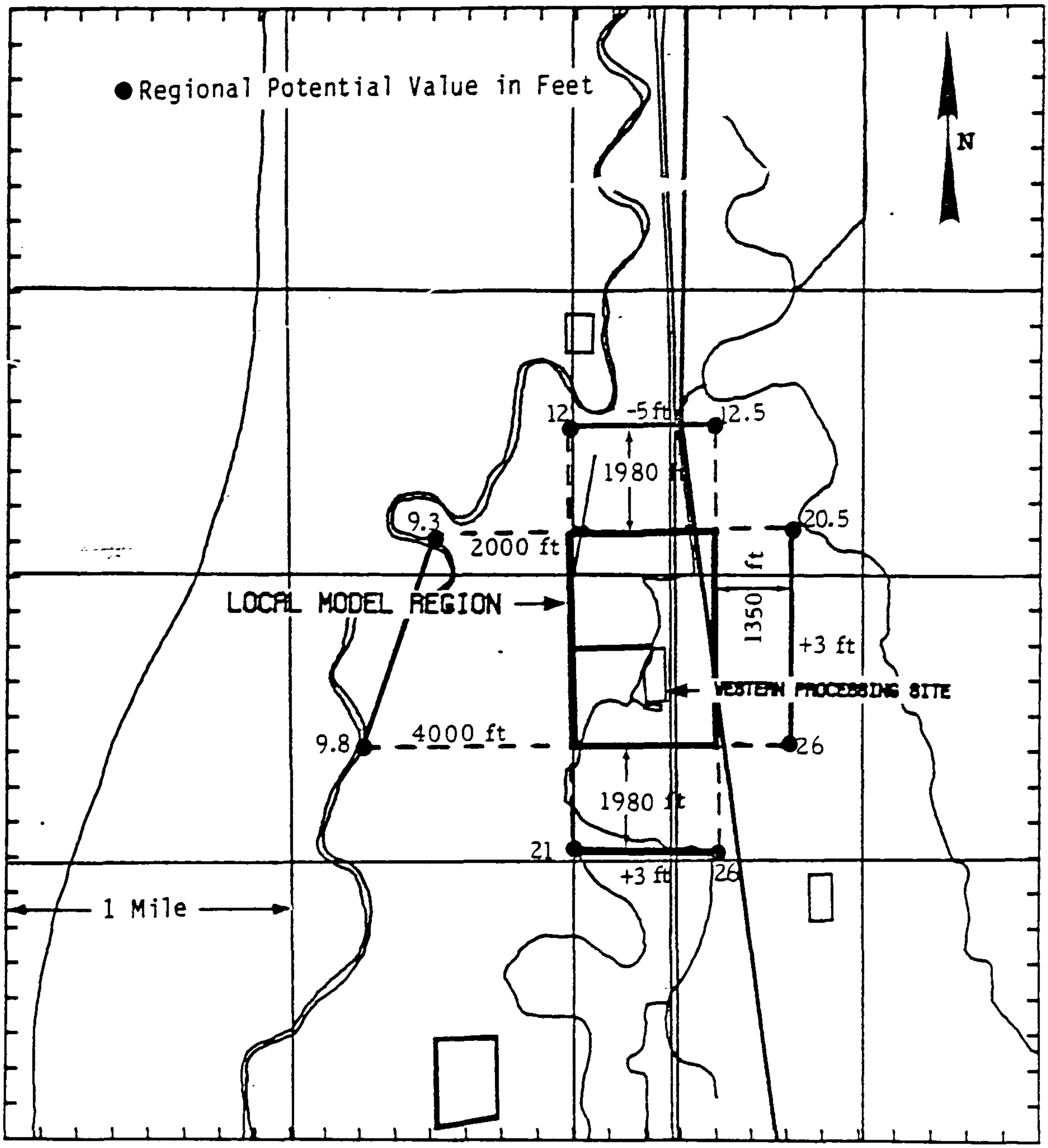

Figure C-1. Locations of Regional Values Used to Determine Boundary Conditions

APPENDIX D

CALCULATION OF RETARDATION FACTOR

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

$$K = 1 + B\ Kd \qquad (D\text{-}1)$$

where B is defined as the bulk density divided by the effective porosity, and Kd is the distribution coefficient. The dry density of the silty sand at the Western Processing Site was estimated as the bulk density of sand (2.6 gm/cm^3) times the quantity 1.0 minus the actual porosity (1.0 - 0.4 = 0.6); or 1.6 gm/cm^3. Kd's for TCE have been reported in the range of 0.1 to 1.0 cm^3/gm (Richter, 1981), depending on the soil type. A Kd of 0.3 cm^3/gm was used to represent the silty sand material at the Western Processing Site.

Using the bulk density for silty sand of 1.6 gm/cm^3 and an effective porosity of 15%, yields a value of 10.7 for B. Substituting B and Kd into equation D-1 yields a K of 4.2, which means that the TCE travels about four times slower than the groundwater.

This value of K was used as a guide in determining the retardation factor to use in the final calibrated CFEST model.

ANALYSIS OF THE WESTERN PROCESSING MODEL SENSITIVITY USING LATIN HYPERCUBE SAMPLING

To better understand Battelle's groundwater flow and contaminant transport model of the Western Processing Site, a sensitivity analysis was performed using Latin Hypercube Sampling (LHS). LHS is a constrained sampling scheme which selects values within a specified range and distribution (Iman and Shortencarier, 1984). These values can then be used as model input parameters so that the correlation between the tested input parameters and the model results can be determined.

A Latin Hypercube Sample is a multiparameter (multivariate) sample composed of a number of replications of individual realizations of the multiparameter set. Each individual parameter is assigned to a probability distribution (normal, lognormal, uniform, loguniform, triangular, beta, or user-defined). The range of each probability distribution is partitioned into a number of equally probable intervals; a uniform distribution is divided into a number of intervals of equal length. LHS involves selecting a parameter value for each of the equally probable intervals (according to the conditional distribution of that interval) and then randomly permuting the orders of intervals in order to introduce the proper degree of correlation between parameters. The main advantage of LHS is that the entire range of the parameter is sampled in an efficient manner.

The LHS technique was applied to analyze the sensitivities of five parameters with respect to the conditions at the Western Processing Site. These parameters are: the hydraulic conductivity of Unit 1; the hydraulic conductivity of Unit 2; the effective porosity; the recharge; and the retardation factor for trichloroethylene (TCE). The sampling range and distribution for each parameter are shown in Table 1. These distributions were input into the LHS program which generated 25 realizations of these parameters (Table 2). These parameter realizations were then input into CFEST to create 25 realizations of the model output. Note that the source strength and dispersivity were not analyzed in this study.

Table 1. Range and Distribution of Parameters Used in LHS Analysis

Parameter	Range	Distribution
Hydraulic Conductivity (Unit 1)	1 to 10 ft/day	Uniform
Hydraulic Conductivity (Unit 2)	10 to 100 ft/day	Uniform
Porosity	10% to 35%	Uniform
Recharge	6 in./yr to 12 in./yr	Uniform
Retardation Factor	2 to 8	Uniform

Table 2. Western Processing Sensitivity (Latin Hypercube Sample Input Vectors)

Run No.	K* Unit 1 x (1)	K* Unit 2 x (2)	Porosity x (3)	Recharge in/yr x (4)	Retardation x (5)
1	1.40	60.0	0.318	11.1	7.54
2	6.26	21.9	0.147	10.5	7.85
3	6.80	47.5	0.169	10.6	4.30
4	9.31	96.8	0.227	7.24	4.78
5	4.07	55.1	0.306	8.91	4.04
6	5.30	75.5	0.261	7.82	7.13
7	6.47	19.3	0.320	6.47	3.58
8	3.62	84.5	0.280	8.52	6.49
9	1.00	90.1	0.123	10.8	4.57
10	2.42	16.6	0.237	9.50	2.90
11	9.27	93.9	0.172	9.28	5.31
12	7.72	70.4	0.246	7.05	7.41
13	7.24	28.5	0.135	8.26	6.29
14	1.95	37.4	0.218	6.70	5.38
15	3.08	73.2	0.186	6.01	2.20
16	4.86	12.8	0.159	8.66	5.63
17	7.98	64.7	0.252	6.96	6.62
18	5.34	52.6	0.194	9.71	5.87
19	8.85	41.0	0.341	11.5	5.03
20	9.88	27.9	0.107	9.92	3.70
21	2.59	45.3	0.206	7.66	3.21
22	3.47	86.5	0.119	11.6	2.99
23	4.57	62.4	0.298	10.2	6.94
24	5.73	79.0	0.286	8.16	2.34
25	8.52	33.9	0.339	12.0	2.66

* ft/day

The MINITAB statistical package was used to analyze the relationship between parameter input and model results. The C classifications used in MINITAB are shown in Table 3. Histograms (which show the distribution of the model results) and descriptive statistics of the model outputs (1983 concentrations, flux to Mill Creek, and total mass of TCE in the groundwater system) are shown in Tables 4 and 5, respectively. The histograms and descriptive statistics indicate that the overall changes in input result in less than an order of magnitude change in model-predicted 1983 source concentrations. But these changes do result in order of magnitude changes in Mill Creek flux and predicted 1983 Mill Creek concentrations.

The model results were regressed upon values of the input parameters (Apppendix A). The regressions were analyzed by comparing the t-statistics (t-ratio) for the regression equations. A summary of the regression t-statistics is shown in Table 6. A higher absolute value of the t-statistic indicates a greater correlation between the parameters. For example, in Table 6 the highest t-statistic for the flux to Mill Creek is for the hydraulic conductivity of Unit 1. Therefore, the flux to Mill Creek is primarily controlled by the conductivity of Unit 1. In this example, the conductivity of Unit 2 has the next highest t-statistic and therefore is the secondary controlling factor. T-statistics with absolute values less than two are considered insignificant. Examination of t-statistics for the input parameters indicates that the parameter with the greatest effect on the model results is the hydraulic conductivity of Unit 1. The results of the regression analysis for each of the model output variables are discussed below.

The predicted 1983 concentration at Well 21 is primarily controlled by the hydraulic conductivity of Unit 1, followed by the retardation factor, effective porosity, and recharge. The predicted 1983 concentration at Reaction Pond I is almost entirely controlled by the hydraulic conductivity of Unit 1 with little or no influence from the other parameters. The dominance of the Unit 1 hydraulic conductivity indicates that the hydraulics (the conductivity and gradient) are dominating the

Table 3. Key to C Classifications

C1 = 1983 TCE Concentration at Well 21 (ppb)

C2 = 1983 TCE Concentration at Reaction Pond I (ppb)

C3 = 1983 TCE Concentration at Reaction Pond III (ppb)

C4 = Flux to Mill Creek (cfs)

C5 = 1983 TCE Concentration in Mill Creek (ppb)

C6 = Hydraulic Conductivity of Unit 1 (ft/day)

C7 = Hydrauilc Conductivity of Unit 2 (ft/day)

C8 = Porosity

C9 = Recharge (ft/day)

C10 = Retardation

C11 = 1968 Total Mass of TCE in Groundwater System

C12 = 1973 Total Mass of TCE in Groundwater System

C13 = 1978 Total Mass of TCE in Groundwater System

C14 = 1983 Total Mass of TCE in Groundwater System

C15 = 1988 Total Mass of TCE in Groundwater System

C16 = 1993 Total Mass of TCE in Groundwater System

C17 = 1998 Total Mass of TCE in Groundwater System

C18 = 2003 Total Mass of TCE in Groundwater System

Table 4. Histograms of Model Results

MTB > HIST C1

Histogram of C1   N = 25
(1983 TCE Concentration at Well 21)

Midpoint	Count	
250000	7	*******
300000	5	*****
350000	5	*****
400000	2	**
450000	0	
500000	0	
550000	3	***
600000	1	*
650000	1	*
700000	1	*

MTB > HIST C2

Histogram of C2   N = 25
(1983 TCE Concentration at Reaction Pond I)

Midpoint	Count	
60000	5	*****
80000	6	******
100000	4	****
120000	4	****
140000	0	
160000	2	**
180000	2	**
200000	1	*
220000	0	
240000	0	
260000	0	
260000	1	*

MTB > HIST C3

Histogram of C3   N = 25
(1983 TCE Concentration at Reaction Pond III)

Midpoint	Count	
80000	4	****
120000	9	*********
160000	6	******
200000	0	
240000	5	*****
280000	0	
320000	0	
360000	0	
[illegible]		

MTB > HIST C4

Histogram of C4   N = 25
(Flux to Mill Creek)

Midpoint	Count	
0.1	1	*
0.2	1	*
0.3	3	***
0.4	1	*
0.5	4	****
0.6	3	***
0.7	4	****
0.8	1	*
0.9	4	****
1.0	1	*
1.1	2	**

MTB > HIST C5

Histogram of C5   N = 25
(1983 TCE Concentration in Mill Creek)

Midpoint	Count	
20	1	*
40	4	****
60	2	**
80	9	*********
100	0	
120	6	******
140	2	**
160	0	
180	1	*

MTB > HIST C11

Histogram of C11   N = 25
(1968 Total Mass of TCE in System)

Midpoint	Count	
4800	1	*
5200	0	
5600	1	*
6000	3	***
6400	4	****
6800	10	**********
7200	5	*****
7600	1	*

Table 4. (Cont'd).

```
MTB > HIST C12

Histogram of C12   N = 25
(1973 Total Mass of TCE in System)
Midpoint    Count
    6000        1   *
    7000        0
    8000        0
    9000        1   *
   10000        7   *******
   11000        0
   12000        8   ********
   13000        4   ****
   14000        3   ***
   15000        1   *
```

```
MTB > HIST C13

Histogram of C13   N = 25
(1978 Total Mass of TCE in System)
Midpoint    Count
    6000        1   *
    8000        0
   10000        0
   12000        7   *******
   14000        1   *
   16000        7   *******
   18000        5   *****
   20000        3   ***
   22000        1   *
```

```
MTB > HIST C14

Histogram of C14   N = 25
(1983 Total Mass of TCE in System)
Midpoint    Count
    6000        1   *
    8000        0
   10000        0
   12000        2   **
   14000        5   *****
   16000        1   *
   18000        0
   20000        9   *********
   22000        2   **
   24000        3   ***
   26000        1   *
   28000        1   *
```

```
MTB > HIST C15

Histogram of C15   N = 25
(1988 Total Mass of TCE in System)
Midpoint    Count
       0        1   *
    4000        0
    8000        6   ******
   12000        2   **
   16000        9   *********
   20000        2   **
   24000        4   ****
   28000        1   *
```

```
MTB > HIST C16

Histogram of C16   N = 25
(1993 Total Mass of TCE in System)
Midpoint    Count
       0        1   *
    4000        3   ***
    8000        5   *****
   12000        7   *******
   16000        3   ***
   20000        5   *****
   24000        0
   28000        1   *
```

```
MTB > HIST C17

Histogram of C17   N = 25
(1998 Total Mass of TCE in System)
Midpoint    Count
       0        1   *
    4000        7   *******
    8000        6   ******
   12000        5   *****
   16000        1   *
   20000        4   ****
   24000        0
   28000        1   *
```

```
MTB > HIST C18

Histogram of C18   N = 25
(2003 Total Mass of TCE in System)
Midpoint    Count
       0        5   *****
    4000        4   ****
    8000        9   *********
   12000        2   **
   16000        3   ***
   20000        1   *
   24000        1   *
```

Table 5. Descriptive Statistics for Model Results

	WELL 21	REACTION POND I	REACTION POND III	MILL CREEK FLUX	MILL CREEK CONCENTRATION
	C1	C2	C3	C6	C7
N	25	25	25	25	25
MEAN	391701	111454	159548	0.638	88.1
MEDIAN	322803	94962	132970	0.640	81.6
TMEAN	374252	106443	152643	0.637	86.8
STDEV	138385	54375	71768	0.283	38.3
SEMEAN	27677	10875	14354	0.057	7.7
MAX	709421	283913	389244	1.140	188.4
MIN	225303	54238	88675	0.139	17.0
Q3	474029	138981	199807	0.909	120.8
Q1	272914	70451	102434	0.440	60.6

TMEAN = Mean of the trimmed sample (less the upper and lower 5%)
SEMEAN = STDEV/ $\sqrt{N}$
Q3 = Third quartile (75%)
Q1 = First quartile (25%)

Total Mass in the System

	1968	1973	1978	1983	1988	1993	1998	2003
	C11	C12	C13	C14	C15	C16	C17	C18
N	25	25	25	25	25	25	25	25
MEAN	6643	11658	15555	18640	15371	12484	10120	8279
MEDIAN	6831	12170	16377	19664	16233	12818	9706	6998
TMEAN	6678	11760	15701	18785	15433	12395	9869	7910
STDEV	576	1864	3426	5083	6201	6584	6647	6492
SEMEAN	115	373	685	1017	1240	1317	1329	1298
MAX	7502	14722	21595	28164	27936	27005	26002	25039
MIN	4976	6244	6145	5777	1385	0	0	0
Q3	7046	12958	17973	22280	19829	17157	14629	12293
Q1	6243	10200	12633	14228	9652	5213	3772	2307

Table 6. Summary of T-Statistics for Regression Equations

	1983 Well 21 Concentration	1983 Reaction Pond I Concentration	1983 Reaction Pond III Concentration	Mill Creek Flux	1983 Mill Creek Concentration	1983 Total TCE Mass in System
K Unit 1	-12.72	-8.98	-9.73	32.59	11.64	-11.40
K Unit 2	1.16	0.08	0.89	6.47	0.56	-0.76
Porosity	-4.33	-1.59	-2.90	1.29	-7.33	7.34
Recharge	-3.35	0.03	0.37	-1.25	1.25	-1.14
Retardation Factor	-7.27	-1.13	-2.89	0.39	8.95	8.90

transport at this source and the retardation has very little effect. The predicted 1983 concentration of Reaction Pond III is also dominated by the hydraulic conductivity of Unit 1, while the effective porosity and retardation factor affect the concentration to a significant but to lesser degree.

The hydraulic conductivity of Unit 1 dominates the predicted flux to Mill Creek. To a lesser degree, Mill Creek flux is also influenced by the conductivity of Unit 2. The predicted 1983 TCE concentration in Mill Creek is about equally dependent on the conductivity of Unit 1, the retardation factor, and the effective porosity, with the hydraulic conductivity having a slightly greater influence.

Regressions were also performed on the predicted total mass of TCE remaining in the groundwater system and the input parameters. (Note that the mass input was constant but the mass exiting the system is variable.) The total mass in the system is controlled by the hydraulic conductivity of Unit 1 followed by the retardation factor and effective porosity. The conductivity has more control after the sources are no longer active. Comparison of the predicted 1983 concentration at three sources and the total mass remaining in the groundwater system indicates that the total mass of TCE is controlled primarily by Reaction Pond I, followed by Reaction Pond III. Well 21 has no effect on the total mass of TCE in the system. The differences between the contributions of the source areas is probably due to the fact that the Reaction Pond sources discharge to Mill Creek while the Well 21 source may have little effect on Mill Creek.

In summary, the LHS analysis has shown that, of the parameters tested, the model is most sensitive to the hydraulic conductivity of Unit 1. The flux and contaminant loading to Mill Creek, the total mass remaining in the system, and the peak concentration at the source areas are all controlled by the Unit 1 conductivity. Because the hydraulic conductivity of Unit 1 is the major controlling factor, confidence in the conductivity values used as input to the model will result in the greatest reliability in model results. The conductivities used in the model have been verified by field testing (at least in the northern portion of the site), therefore much confidence can be placed in the flow-portion of the model.

APPENDIX A

MINITAB Regression Equations

```
MTB > REGRESS C1 5 C6-C10

The regression equation is
C1 = 998017 - 39189 C6 + 366 C7 - 486287 C8 - 15677 C9 - 33994 C10

Predictor          Coef        Std.Coef      t-ratio
Constant         998017           60591        16.47
C6               -39189            3082       -12.72
C7                366.4           315.8         1.16
C8              -486287          112336        -4.33
C9               -15677            4673        -3.35
C10              -33994            4677        -7.27

S = 40046          R-sq = 93.37%     R-sq(adj) = 91.62%

Analysis of Variance

Source          DF           SS            MS
Regression       5   4.2914E+11    8.5828E+10
Error           19   3.0470E+10    1603698560
Total           24   4.5961E+11
```

```
MTB > REGRESS C2 5 C6-C10

The regression equation is
C2 = 251049 - 17632 C6 + 16 C7 - 115172 C8 + 82 C9 - 3408 C10

Predictor          Coef        Std.Coef      t-ratio
Constant         251049           39044         6.43
C6               -17832            1986        -8.98
C7                 16.4           203.5         0.08
C8              -115172           72388        -1.59
C9                   82            3011         0.03
C10               -3408            3014        -1.13

S = 25805          R-sq = 82.17%     R-sq(adj) = 77.47%

Analysis of Variance

Source          DF           SS            MS
Regression       5   5.8308E+10    1.1662E+10
Error           19   1.2652E+10     665914176
Total           24   7.0961E+10
```

```
MTB > REGRESS C3 5 C6-C10

The regression equation is
C3 = 364534 - 22327 C6 + 208 C7 - 242655 C8 + 1275 C9 - 10048 C10

Predictor         Coef       Std.Coef      t-ratio
Constant        364534          45095         8.08
C6              -22327           2294        -9.73
C7               208.1          235.1         0.89
C8             -242655          83607        -2.90
C9                1275           3478         0.37
C10             -10048           3481        -2.89

S = 29805        R-sq = 86.346     R-sq(adj) = 82.753

Analysis of Variance

Source        DF          SS            MS
Regression     5   1.0674E+11    2.1347E+10
Error         19   1.6878E+10     888308926
Total         24   1.2362E+11



MTB > REGRESS C4 5 C6-C10

The regression equation is
C4 = - 0.0396 + 0.104 C6 + 0.00211 C7 + 0.149 C8  - 0.00604 C9  + 0.00189 C1

Predictor         Coef       Std.Coef      t-ratio
Constant      -0.03959        0.06266        -0.63
C6            0.103867       0.003187        32.59
C7           0.0021131      0.0003266         6.47
C8              0.1493         0.1162         1.29
C9           -0.006036       0.004833        -1.25
C10           0.001888       0.004637         0.39

S = 0.04141      R-sq = 98.299     R-sq(adj) = 97.851

Analysis of Variance

Source        DF          SS            MS
Regression     5     1.88278       0.37656
Error         19     0.03259       0.00172
Total         24     1.91537
```

MTB > REGRESS C5 5 C6-C10

The regression equation is
C5 = 126 + 10.0 C6 + 0.0496 C7 - 230 C8 + 1.64 C9 - 11.7 C10

Predictor	Coef	Std.Coef	t-ratio
Constant	125.80	16.97	7.41
C6	10.0436	0.8630	11.64
C7	0.04957	0.08844	0.56
C8	-230.41	31.45	-7.33
C9	1.641	1.309	1.25
C10	-11.723	1.309	-8.95

S = 11.21 R-sq = 93.2% R-sq(adj) = 91.4%

Analysis of Variance

Source	DF	SS	MS
Regression	5	32753.3	6550.7
Error	19	2388.9	125.7
Total	24	35142.3	

MTB > REGRESS C11 5 C6-C10

The regression equation is
C11 = 5973 - 138 C6 - 0.49 C7 + 3985 C8 - 24.1 C9 + 154 C10

Predictor	Coef	Std.Coef	t-ratio
Constant	5973.3	378.3	15.79
C6	-137.53	19.24	-7.15
C7	-0.486	1.972	-0.25
C8	3984.9	701.4	5.68
C9	-24.07	29.18	-0.82
C10	154.45	29.20	5.29

S = 250.0 R-sq = 85.1% R-sq(adj) = 81.1%

Analysis of Variance

Source	DF	SS	MS
Regression	5	6784025	1356805
Error	19	1187768	62514
Total	24	7971793	

MTB > REGRESS C12 5 C6-C10

The regression equation is
C12 = 9698 - 459 C6 - 3.51 C7 + 12139 C8 - 91.0 C9 + 553 C10

Predictor	Coef	Std.Coef	t-ratio
Constant	9698	1019	9.51
C6	-459.25	51.85	-8.86
C7	-3.513	5.314	-0.66
C8	12139	1890	6.42
C9	-91.03	78.63	-1.16
C10	553.37	78.69	7.03

S = 673.8   R-sq = 89.651   R-sq(adj) = 86.927

Analysis of Variance

Source	DF	SS	MS
Regression	5	74718240	14943648
Error	19	8625659	453982
Total	24	83343896	

MTB > REGRESS C13 5 C6-C10

The regression equation is
C13 = 12002 - 867 C6 - 6.60 C7 + 21635 C8 - 156 C9 + 1043 C10

Predictor	Coef	Std.Coef	t-ratio
Constant	12002	1687	7.11
C6	-866.93	85.79	-10.10
C7	-6.603	8.792	-0.75
C8	21635	3127	6.92
C9	-155.7	130.1	-1.20
C10	1043.3	130.2	8.01

S = 1115   R-sq = 91.620   R-sq(adj) = 89.[illegible]

Analysis of Variance

Source	DF	SS	MS
Regression	5	258161104	51632220
Error	19	23612594	1242768
Total	24	281773696	

```
MTB > REGRESS C14 5 C6-C10

The regression equation is
C14 = 13407 - 1322 C6 - 9.0 C7 + 31008 C8 - 200 C9 + 1566 C10

Predictor         Coef       Std.Coef     t-ratio
Constant         13407           2280        5.88
C6             -1322.4          116.0      -11.40
C7               -9.03          11.88       -0.76
C8               31008           4227        7.34
C9              -200.2          175.8       -1.14
C10             1565.6          176.0        8.90

S = 1507         R-sq = 93.04%    R-sq(adj) = 91.21%

Analysis of Variance

Source          DF         SS            MS
Regression       5     576906944     115381392
Error           19      43144264       2270751
Total           24     620051200



MTB > REGRESS C15 5 C6-C10

The regression equation is
C15 = 8906 - 1667 C6 - 7.1 C7 + 36106 C8 - 181 C9 + 1907 C10

Predictor         Coef       Std.Coef     t-ratio
Constant          8906           2586        3.44
C6             -1667.0          131.5      -12.68
C7               -7.10          13.48       -0.53
C8               36106           4794        7.53
C9              -181.5          199.4       -0.91
C10             1907.1          199.6        9.56

S = 1709         R-sq = 93.98%    R-sq(adj) = 92.40%

Analysis of Variance

Source          DF         SS            MS
Regression       5     867322368     173464480
Error           19      55488452       2920445
Total           24     922810816
```

```
MTB > REGRESS C16 5 C6-C10

The regression equation is
C16 = 5543 - 1826 C6 - 0.6 C7 + 35869 C8 - 105 C9 + 1979 C10

Predictor        Coef       Std.Coef     t-ratio
Constant         5543         2844          1.95
C6            -1826.1        144.6        -12.62
C7              -0.61        14.62         -0.04
C8              35869         5273          6.80
C9             -105.0        219.3         -0.48
C10            1979.2        219.5          9.02

S = 1880         R-sq = 93.548     R-sq(adj) = 91.850

Analysis of Variance

Source        DF          SS            MS
Regression     5    973102464     194620496
Error         19     67119336       3532597
Total         24   1040221824


MTB > REGRESS C17 5 C6-C10

The regression equation is
C17 = 2925 - 1884 C6 + 8.9 C7 + 33023 C8 + 4 C9 + 1920 C10

Predictor        Coef       Std.Coef     t-ratio
Constant         2925         3302          0.89
C6            -1883.7        167.9        -11.22
C7               8.86        17.21          0.51
C8              33023         6121          5.39
C9                4.5        254.7          0.02
C10            1920.3        254.8          7.54

S = 2182         R-sq = 91.468     R-sq(adj) = 89.223

Analysis of Variance

Source        DF          SS            MS
Regression     5    970004544     194000912
Error         19     90478456       4762024
Total         24   1060483008
```

```
MTB > REGRESS C18 5 C6-C10

The regression equation is
C18 = 783 - 1872 C6 + 21.0 C7 + 28975 C8 + 143 C9 + 1766 C10

Predictor         Coef       Std.Coef      t-ratio
Constant           783           3624         0.22
C6             -1871.6          184.3       -10.15
C7               21.00          18.89         1.11
C8               28975           6719         4.31
C9               143.4          279.5         0.51
C10             1766.0          279.7         6.31

S = 2395          R-sq = 89.22%     R-sq(adj) = 86.38%

Analysis of Variance

Source          DF           SS          MS
Regression       5    902565760   180513152
Error           19    108997848     5736729
Total           24   1011563584


MTB > REGRESS C14 3 C1-C3

The regression equation is
C14 = 16292 + 0.0009 C1 + 0.308 C2 - 0.203 C3

Predictor         Coef       Std.Coef      t-ratio
Constant         16292           1955         8.33
C1             0.00085        0.01201         0.07
C2             0.30807        0.06225         4.95
C3            -0.20253        0.05936        -3.41

S = 3200          R-sq = 65.32%     R-sq(adj) = 60.36%

Analysis of Variance

Source          DF           SS          MS
Regression       3    405033836   135011250
Error           21    215017360    10238922
Total           24    620051200

Source          DF       Seq SS
C1               1     23078470
C2               1    262764656
C3               1    119190712
```

MTB > REGRESS C14 2 C5 C6

The regression equation is
C14 = 30298 - 134 C5 + 22.8 C6

Predictor	Coef	Std.Coef	t-ratio
Constant	30298.4	92.7	326.58
C5	-133.786	1.221	-109.60
C6	22.79	17.54	1.30

S = 173.8 R-sq = 99.89% R-sq(adj) = 99.88%

Analysis of Variance

Source	DF	SS	MS
Regression	2	619386752	309693376
Error	22	664470	30203
Total	24	620051200	

Source	DF	Seq SS
C5	1	619335744
C6	1	51007

MTB > REGRESS C14 2 C4 C5

The regression equation is
C14 = 30317 + 67 C4 - 133 C5

Predictor	Coef	Std.Coef	t-ratio
Constant	30316.6	100.0	303.04
C4	65.7	162.9	0.41
C5	-133.052	1.202	-110.66

S = 179.7 R-sq = 99.89% R-sq(adj) = 99.87%

Analysis of Variance

Source	DF	SS	MS
Regression	2	619341184	309670592
Error	22	710057	32275
Total	24	620051264	

Source	DF	Seq SS
C4	1	224095344
C5	1	395245792

WESTERN PROCESSING
HYDROLOGIC CHARACTERIZATION

by

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March, 1985

Prepared for
Environmental Protection Agency
Region X
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WESTERN PROCESSING HYDROLOGIC CHARACTERIZATION

Slug tests and borehole dilution tests were performed at the Western Processing Site (Figure 1) to better characterize the groundwater flow system. The tests were performed during the period February 11-13, 1985, by Jim Doesburg, Mary Lilga, and Chris Eddy of Battelle's Office of Hazardous Waste Management. The results indicate that hydraulic conductivities of the zones tested range from 5 x 10^{-2} cm/sec (142 ft/day) to 4 x 10^{-4} cm/sec (1 ft/day). The test procedures and results are discussed below. The field forms and plots used to calculate the hydraulic conductivity are included in Appendices A and B, respectively.

SLUG TEST PROCEDURES

The hydraulic conductivity of an aquifer can be determined by instantaneously changing the water level in a well and observing the recovery. For the Western Processing Site, a 3.5-in. diameter slug was used to change the water level. The slug was designed to displace the water 5,408 cm^3, which should result in a 66-cm change in water level in a 4-in. diameter well. The recovery was measured after both inserting and removing the slug using an electrical tape.

The change in water level over time was then plotted on semi-log paper and the method described in Bouwer and Rice (1976) was used to analyze the results.

SLUG TEST RESULTS

A summary of the slug test results is shown in Table 1. Four zones of permeabilities could be discerned. Conductivities vary between the shallow and deep portions of the aquifer, and the north and south portions of the site. The shallow portion of the aquifer in the north of the site has a conductivity of about 10^{-3} cm/sec (3 ft/day), while the deep portion has a conductivity of about 4 x 10^{-2} cm/sec (113 ft/day). The

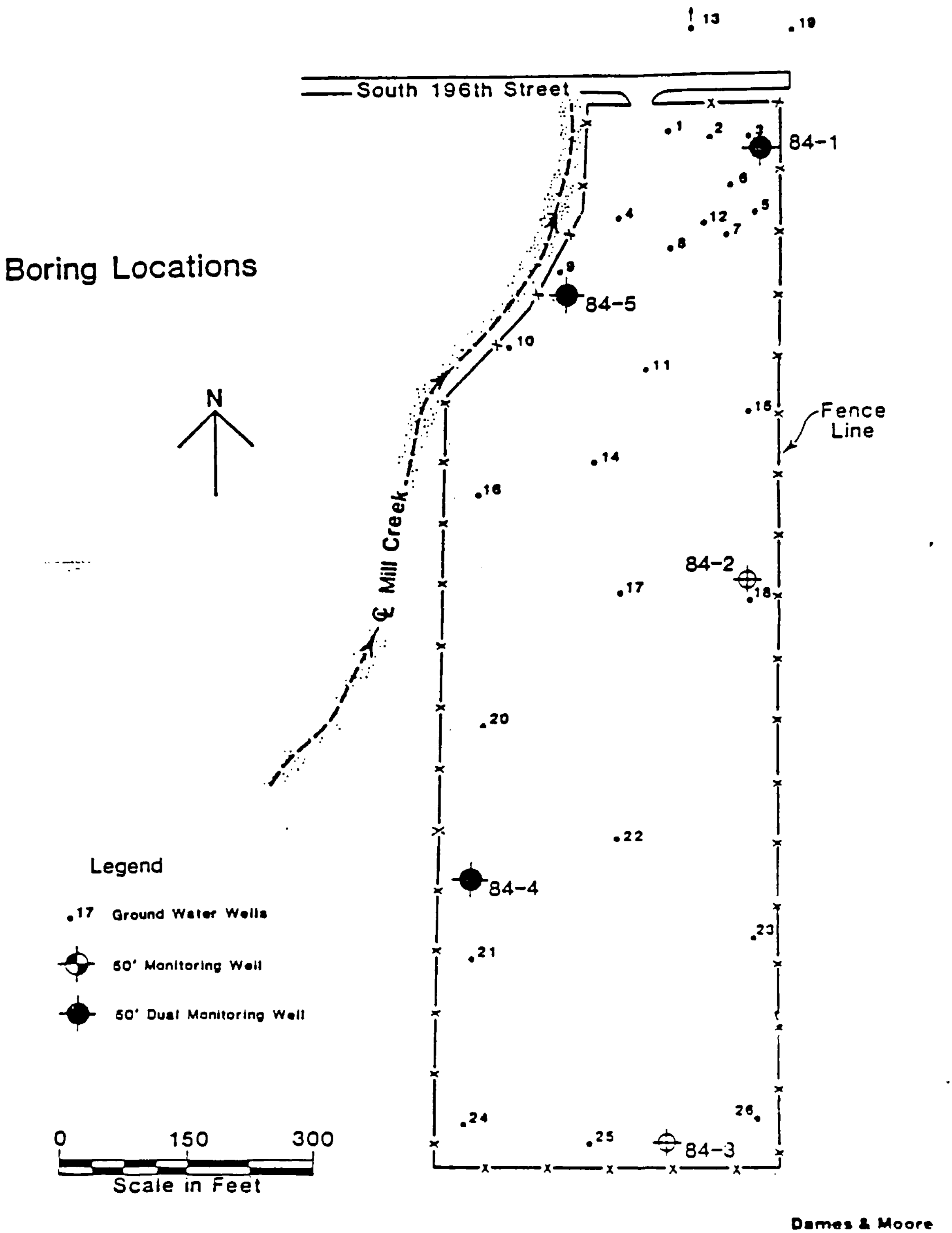


Figure 1. Western Processing Well Locations

opposite is true of the southern portion of the site; the deep portion of the aquifer has a conductivity of about 3×10^{-3} cm/sec (8.5 ft/day), while the shallow portion is approximately 2×10^{-2} cm/sec (57 ft/day). The values for conductivity can be quantitatively verified by comparing the calculated values with the geology of the screened interval (Table 2). The fine-to-medium sand has a conductivity of 3×10^{-2} cm/sec (85 ft/day), while the presents of peat, clay, and/or silt decreased the conductivity to 6×10^{-4} cm/sec (1.7 ft/day).

Table 1. Summary of Slug Test Results

Well No.	Hydraulic Conductivity (cm/sec)*
1A	2×10^{-3}
1B	8×10^{-4}
17A	6×10^{-4}
84-1B	2×10^{-2}
84-2	9×10^{-4}
84-3	8×10^{-3}
84-4A	2×10^{-2}
84-4B	4×10^{-4}
84-5A	4×10^{-4}
84-5B	5×10^{-2}

*Average of the results for dropping and removing the slug (see Appendix B).

Table 2. Comparison of Hydraulic Conductivity and Lithology

Well No.	Depth	Conductivity (cm/sec)	Lithology
1A	15 ft	2×10^{-3}	Sand with Silt/Clay Lenses
17A	15 ft	6×10^{-4}	Silt and Clay
84-4A	25 ft	2×10^{-2}	Fine-to-Medium Sand
84-5A	25 ft	4×10^{-4}	Peat/Fine-to-Medium Sand
1B	30 ft	8×10^{-4}	Peat/Fine Sand
84-1B	50 ft	2×10^{-2}	Fine-to-Medium Sand
84-2	50 ft	9×10^{-4}	Fine Silty Sand
84-3	50 ft	8×10^{-3}	Fine-to-Coarse Sand
84-4B	50 ft	4×10^{-4}	Sandy Silt
84-5B	50 ft	5×10^{-2}	Fine-to-Medium Sand

The values for conductivity used in Battelle's groundwater flow and contaminant transport model of the Western Processing Site were 1.2×10^{-3} cm/sec (3.5 ft/day) for the upper 30 ft, and 1.8×10^{-2} cm/sec (50 ft/day) for the portion of the aquifer below 30 ft. The values closely match the values obtained from the slug tests in the northern portion of the site, while these values vary an order of magnitude in the southern portion of the site. Since the majority of the contaminants of interest in the model were disposed of in the northern portion (Reaction Ponds I and III) of the site, the difference between the model predicted and measured hydraulic conductivities will probably have little effect on the overall transport of contaminants.

BOREHOLE DILUTION TEST PROCEDURES

Borehole dilution testing as described by Freeze and Cherry (1979) has been used extensively in Europe on a means of determining groundwater velocity. The theory is that the horizontal velocity of groundwater through a well-bore can be determined by measuring the change in concentration over time of a specific ion introduced into the borehole. This measurement is performed by packing off a known portion of a screen, introducing a known ion, and measuring the changes in concentration over time. Figure 2 is a schematic of the apparatus used at the Western Processing Site.

BOREHOLE DILUTION TEST RESULTS

The borehole dilution tests met with mixed results. Several equipment problems and difficult field conditions resulted in tests being performed on only two boreholes. Both Battelle pumps refused to work (both were lab tested prior to field work), and the conductivity meter would not function properly. The conductivity meter gave anomolous measurements when the probe was moved near the lower mixing tube. When the probe was moved near the upper mixing tube, the anomolous measurements ceased (see

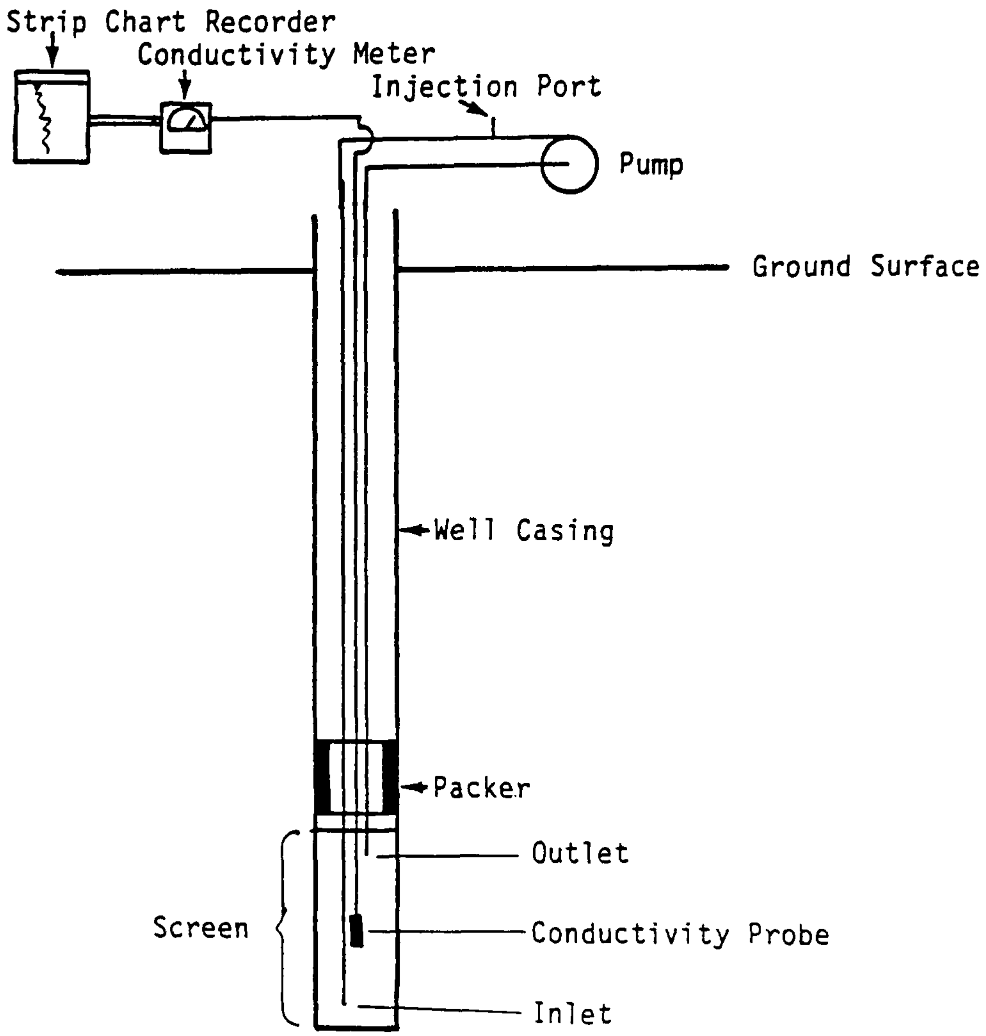


Figure 2. Borehole Dilution Test Apparatus

Figure 2). We obtained a third pump from the EPA Manchester lab which did work. Further modifications have been made to the test apparatus to eliminate the probe problem in the future.

The tests that were performed did show the expected change in conductance with time. Because of the errors in the initial readings, the calculated velocities were suspect. The borehole tests indicated that horizontal groundwater flow near Well 17A was much less than that of Well 1B. Unfortunately, the length of time that was required to complete the test at Well 17A was longer than the time available on site.

REFERENCES

Bouwer, H., and R. C. Rice. 1976. "A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells." Water Resources Research, Vol. 12, No. 3, pp. 423-428.

Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, NJ.

APPENDIX A

SLUG TEST FIELD FORMS

SITE Western Processing

SLUG TEST FIELD FORM

Date 2/11/85 10:30

Investigator J. Doesburg

C. Eddy

M. Lilga

Borehole # 1A

Radius of borehole 4 in./10 cm

Radius of casing 2 in./5 cm

Depth of well 443 cm

Length of screen 3 ft./91 cm

Reference point for water level measurments Top of PVC Casing

Elevation Steel Casing 23.38 ft. AMSL 713 cm

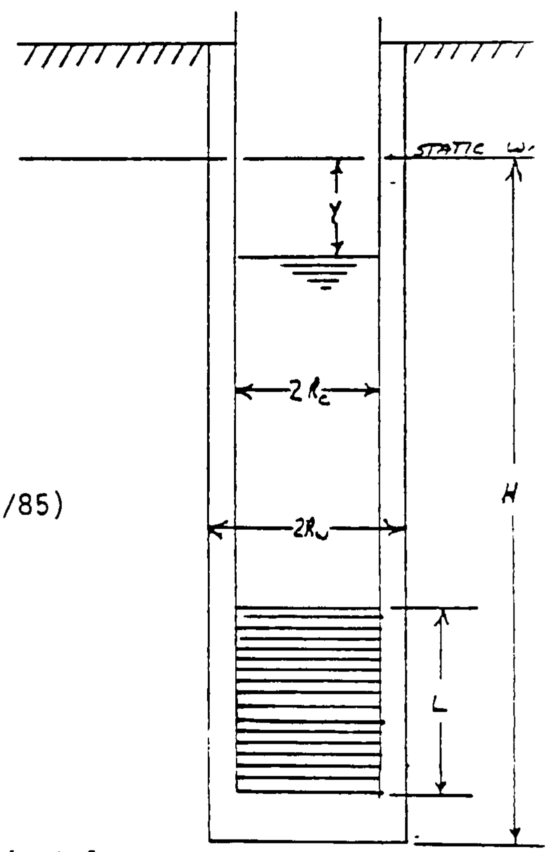
Static water level 250 cm (2/11/85)-246.5 cm (2/13/85)

Static water level elevation ~466 cm

Ground surface elevation NA

Slug volume 330 cu. in. /5408 cm^3

Anticipated displacement 26 in./66 cm



Remarks: * Stop watch had to be restarted at approximately 30 minutes.

This well was installed with a backhoe (F. Wolf verbal communication). There is a large gravel pack around the screen.

Water level in well dropped 21 cm overnight. Reading 8:30 a.m.-2/12/85. Puddles which had been 6" deep in vicinity were gone in morning.

WELL # 1A

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
					20	6:00	242.75	7.25	
					21	7:00	243	7	
	DROPPING SLUG				22	9:00	243.5	6.5	
1	0:00	250	0		23	11:00	244	6	
2	0:05	221	29		24	15:00	244	6	
3	0:15	229	21		25	20:00	245	5	
4	0:25	232	18		26	25:00	244.5	5.5	
5	0:35	234	16		27	* SEE REMARK 35:00	244.5	5.5	
6	0:45	237	13		28	45:00	244.5	5.5	
7	0:60	237.5	12.5		29	2:52:00	250	0	
8	1:15	238.5	11.5			REMOVING SLUG			
9	1:30	239	11		1	0:15	267	17	
10	1:45	240	10		2	0:30	257	7	
11	2:00	240.5	9.5		3	0:40	252.5	2.5	
12	2:15	241	9		4	0:50	251	1	
13	2:30	241.5	8.5		5	1:00	249	-1	
14	2:45	241.5	8.5		6	1:10	148	-2	
15	3:00	242	8		7	1:20	246.5	-3.5	
16	3:30	242.5	7.5		8	1:30	245.5	-4.5	
17	4:00	242.5	7.5		9	1:40	244.5	-5.5	
18	4:30	242.5	7.5		10	1:50	244	-6	
19	5:00	242.75	7.25		11	2:05	242.5	-7.5	

WELL # 1A

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
12	2:15	242.5	-7.5		34	1:10:00	235	-15	
13	2:30	242	-8		35	1:29:00	236	-14	
14	2:45	241	-9		36	1:46:00	236	-14	
15	3:00	241	-9		37	18:26:00	257	7	
16	3:15	241	-9						
17	3:30	241	-9						
18	4:00	240	-10						
19	4:30	239	-11						
20	5:00	238	-12						
21	5:30	237.5	-12.5						
22	6:00	236.5	-13.5						
23	7:00	235	-15						
24	8:00	234.5	-15.5						
25	10:00	234	-16						
26	12:00	234	-16						
27	14:00	234	-16						
28	17:00	234	-16						
29	22:00	233.5	-16.5						
30	28:00	233.5	-16.5						
31	47:30	235	-15						
32	57:00	234	-16						

WELL # 1A

SLUG TEST FIELD FORM

RETEST

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
1	0:00	246.5	0		23	8:00	245	1.5	
2	0:05	217:5	29		24	9:00	245.2	1.3	
3	0:16	225	21.5		25	10:00	245.3	1.2	
4	0:24	228	18.5		26	12:00	245.5	1.0	
5	0:31	230	16.5		27	14:00	245.8	.7	
6	0:39	232	14.5		28	17:00	245.9	.6	
7	0:47	233.5	13		29	20:07	245.9	.6	
8	0:57	235	11.5		30	3:30:39	246	0	
9	1:10	237	9.5			SLUG REMOVED			
10	1:22	238	8.5		1	0:16	259.5	13	
11	1:35	239	7.5		2	0:27	259.5	13	
12	2:00	240	6.5		3	0:40	259.5	13	
13	2:20	241	5.5		4	0:55	259	12.5	
14	2:40	242	4.5		5	1:13	257.5	11	
15	3:00	242	4.5		6	1:30	256.5	10	
16	3:30	242.5	4		7	1:45	256.5	10	
17	4:00	243	3.5		8	2:00	255.5	9	
18	4:30	243.5	3		9	2:20	255	8.5	
19	5:00	244	2.5		10	2:40	254	7.5	
20	5:45	244	2.5		11	3:00	253.5	7	
21	6:30	244.5	2		12	3:20	253	6.5	
22	7:15	245	1.8		13	3:40	252.5	6	

WELL # 1A

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
14	4:00	25.2	5.5						
15	4:30	251.5	5						
16	5:00	251	4.5						
17	5:45	250.5	4						
18	6:30	249.5	3						
19	7:15	249	2.5						
20	8:00	248.5	2						
21	9:00	248	1.5						
22	10:00	248	1.5						
23	11:00	247.5	1						
24	13:40	247	1						
25	15:00	247	1						
26	17:00	246.7	.2						

SITE Western Processing

SLUG TEST FIELD FORM

Date 2/11/85 10:00

Investigator J. Doesburg

C. Eddy

M. Lilga

Borehole # 1B

Radius of borehole 10 cm

Radius of casing 5 cm

Depth of well 914 cm

Length of screen 91 cm

Reference point for water level measurments Top of PVC Casing

Elevation Steel Casing 788 cm AMSL

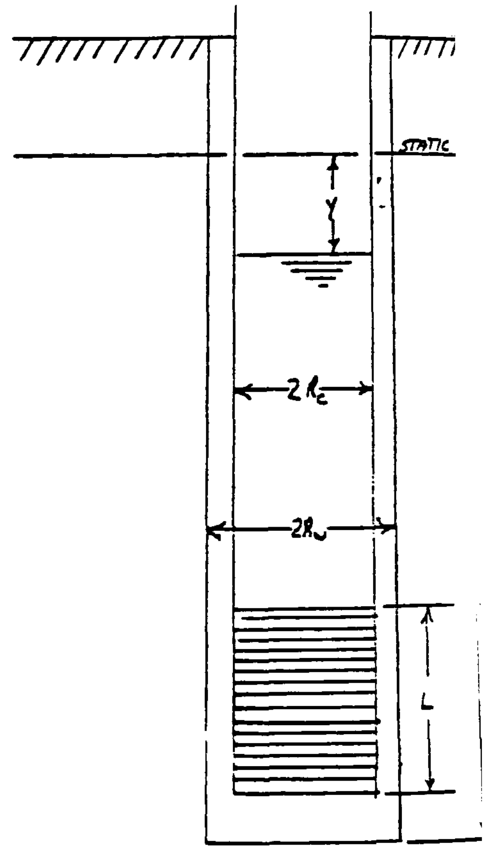
Static water level 276 cm

Static water level elevation ~512 cm

Ground surface elevation NA

Slug volume 330 cu. in./5408 cm^3

Anticipated displacement 66 cm



Remarks: Cold, wet. Intemittent rain.

WELL # 1B

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
					20	3:40	247.5	28.5	
					21	4:00	249	27	
	DROPPING SLUG				22	4:30	251	25	
1	0:00	276	0		23	5:00	253	23	
2	0:05	217	59		24	5:30	254.5	21.5	
3	0:15	218	58		25	6:00	256	20	
4	0:25	220	56		26	7:00	259	17	
5	0:35	222	54		27	8:00	261.5	14.5	
6	0:45	224	52		28	9:00	264	13	
7	0:55	228	48		29	10:00	265	11	
8	1:05	228	48		30	12:00	268	8	
9	1:15	230	46		31	14:00	269	7	
10	1:25	231	45		32	16:00	271	5	
11	1:35	233	43		33	18:00	272.5	3.5	
12	1:45	234	42		34	20:00	273.5	2.5	
13	1:55	235	41		35	22:00	275	1	
14	2:05	237	39		36	24:00	275	1	
15	2:20	239	37		37	26:00	275.5	.5	
16	2:40	242	34		38	28:00	276	0	
17	2:55	243	33						
18	3:10	244	32						
19	3:25	246	30						

SITE Westerm Processing

SLUG TEST FIELD FORM

Date 2/11/85 09:00

Investigator J. Doesburg

C. Eddy

M. Lilga

Borehole # 11A

Radius of borehole 10 cm

Radius of casing 5 cm

Depth of well 457 cm

Length of screen 91 cm

Reference point for water level measurments Top of PVC Casing

Elevation Steel Casing 767 cm AMSL

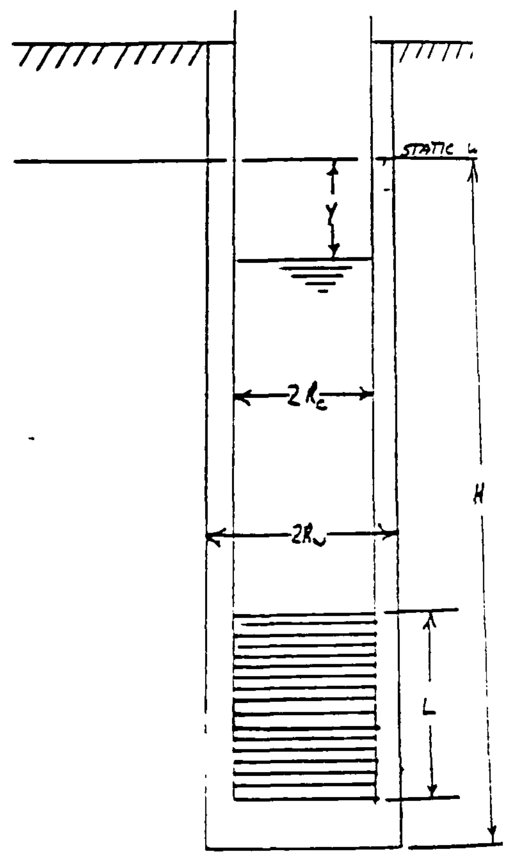
Static water level 284 cm

Static water level elevation ~483 cm

Ground surface elevation NA

Slug volume 330 cu. in./5408 cm^3

Anticipated displacement 66 cm



Remarks: Recovery in about 5 seconds.
Maximum displacement about 8 cm.

Using 8 cm as y_o and .1 and 5 sec. at y_o and t gives a K of 2×10^{-1} cm/sec.

Well 11B PVC casing is broken.

SITE Western Processing

SLUG TEST FIELD FORM

Date 2/12/85 08:50

Investigator J. Doesburg
C. Eddy
M. Lilga

Borehole # 17A

Radius of borehole 10 cm

Radius of casing 5 cm

Depth of well 524 cm

Length of screen 91 cm

Reference point for water level measurments Top of PVC Casing-East Side(PVC Cut on Slant)

Elevation Steel Casing 741 cm AMSL

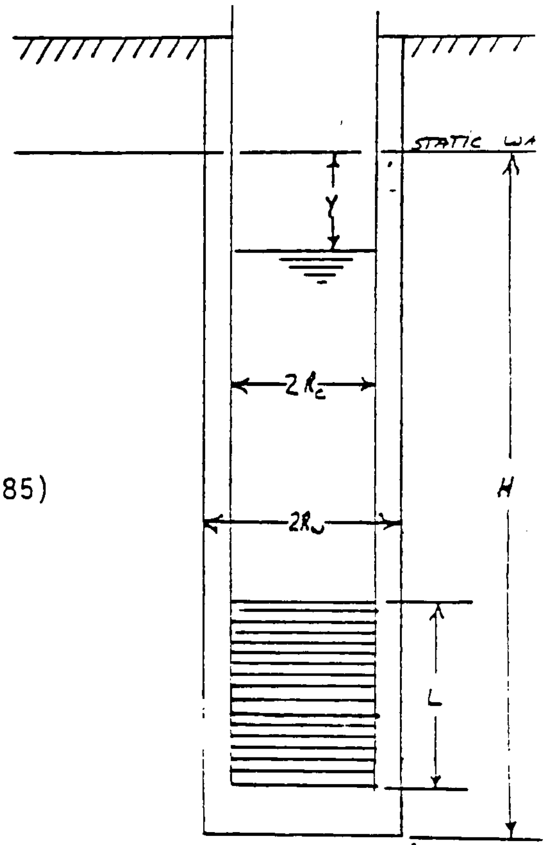
Static water level 196 cm (2/11/85) 205 cm (2/12/85)

Static water level elevation ~536 cm

Ground surface elevation NA

Slug volume 330 cu. in./5408 cm^3

Anticipated displacement 66 cm



Remarks: 2/11/85 Raining
2/12/85 Sunny

Well 17B has screwed joints.

WELL # 17A

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
	DROPPING SLUG			
1	0:00	205	0	
2	0:05	142	63	
3	0:15	147	58	
4	0:30	151.5	53.5	
5	0:40	153.5	51.5	
6	0:45	156	49	
7	0:55	158	47	
8	1:10	162	43	
9	1:25	164.5	41.5	
10	1:35	167	38	
11	1:45	168	37	
12	2:00	170	35	
13	2:10	171	34	
14	2:20	173	32	
15	2:35	176	29	
16	2:50	178	27	
17	3:00	178.5	26.5	
18	3:10	180	25	
19	3:30	181	24	

#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
20	3:40	182	23	
21	3:55	184	21	
22	4:10	185	20	
23	4:25	186	19	
24	4:35	187	18	
25	4:55	190	15	
26	5:15	191	14	
27	5:25	191.5	13.5	
28	5:40	192	13	
29	6:00	193	12	
30	6:30	195	10	
31	7:00	196	9	
32	7:30	197.5	7.5	
33	8:00	198	7	
34	8:30	198.5	6.5	
35	9:00	200	5	
36	9:30	200.5	4.5	
37	10:00	201	4	
38	11:00	202	3	
39	12:00	202.5	2.5	
40	13:00	203	2	
41	14:45	203	2	

WELL # 17A

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
42	16:00	203.5	1.5		13	3:00	259	54	
43	17:00	204	1		14	3:20	258.5	53.5	
44	18:00	204	1		15	3:50	256.5	51.5	
45	20:00	204	1		16	4:10	255.5	50.5	
46	22:00	204	1		17	4:30	255	50	
47	25:00	204	1		18	5:00	253	48	
48	30:00	204	1		19	5:30	252	47	
49	35:00	204	1		20	6:00	250.5	45.5	
50	51:00	204	1		21	6:30	249	44	
	REMOVING SLUG				22	7:15	247	42	
1	0:08	274	69		23	8:00	246	41	
2	0:25	269	64		24	9:00	243.5	38.5	
3	0:40	267	62		25	10:00	241	36	
4	0:50	267	62		26	11:00	240	35	
5	1:00	266	61		27	12:00	237	32	
6	1:15	266	61		28	13:00	235.5	30.5	
7	1:30	265	60		29	14:00	234	29	
8	1:45	263	58		30	15:30	231	26	
9	2:00	262	57		31	17:00	229	24	
10	2:10	261.5	56.5		32	18:30	227.5	22.5	
11	2:30	260.5	55.5		33	20:00	226	21	
12	2:45	259.5	54.5		34	22:00	224	19	

WELL # 17A

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
35	24:00	221.5	16.5						
36	27:00	219	14						
37	30:00	216.5	11.5						
38	35:00	214	9						
39	40:00	212	7						
40	50:00	209	4						
41	1:46:00	205	at 11:35 actual time						
	Stop watch reset at time 10:53, stop watch time 1:04								

SITE Western Processing

SLUG TEST FIELD FORM

Date 2/12/85

Investigator J. Doesburg

C. Eddy

M. Lilga

Borehole # 17B

Radius of borehole 10 cm

Radius of casing 5 cm

Depth of well 914 cm

Length of screen 91 cm

Reference point for water level measurments Top of PVC Casing

Elevation Steel Casing 736 cm AMSL

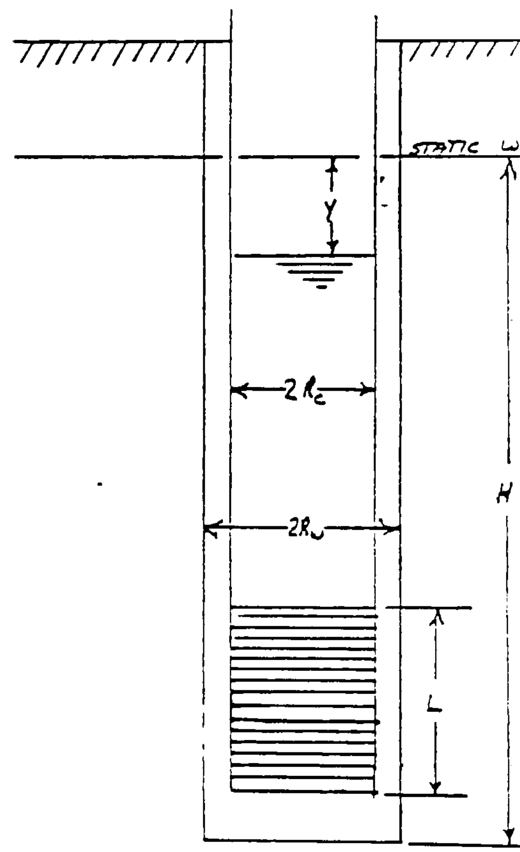
Static water level 285 cm

Static water level elevation ~ 451 cm

Ground surface elevation NA

Slug volume 330 cu. in./5408 cm^3

Anticipated displacement 66 cm



Remarks: Joints are screwed together so slug won't fit in hole.

SITE Western Processing

SLUG TEST FIELD FORM

Date 2/13/85

Investigator C. Eddy

M. Lilga

Borehole # 84-1-A

Radius of borehole 10 cm

Radius of casing 5 cm

Depth of well 762 cm

Length of screen 152 cm

Reference point for water level measurments Top of PVC

Casing

Elevation NA

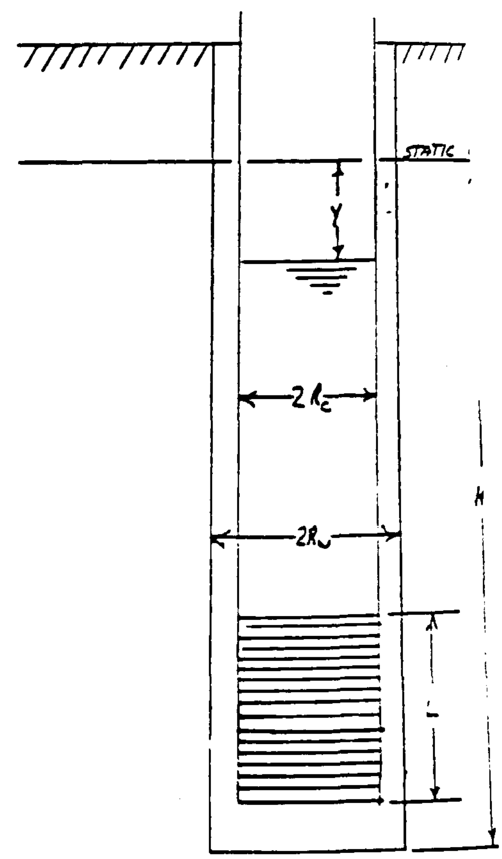
Static water level 302 cm

Static water level elevation NA

Ground surface elevation NA

Slug volume 330 cu. in. /5408 cm^3

Anticipated displacement 66 cm



Remarks: Unable to slug test due to presence of screws in casing.

SITE Western Processing

SLUG TEST FIELD FORM

Date 2/13/85

Investigator C. Eddy

M. Lilga

Borehole # 84-1-B

Radius of borehole 10 cm

Radius of casing 5 cm

Depth of well 1524 cm

Length of screen 152 cm

Reference point for water level measurments Top of PVC

Casing

Elevation NA

Static water level 321.5 cm

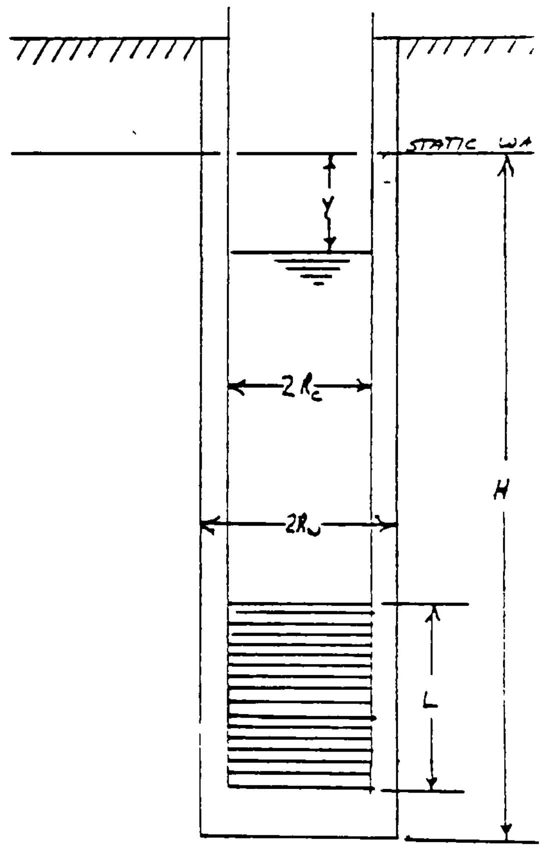
Static water level elevation NA

Ground surface elevation NA

Slug volume 330 cu. in./5408 cm^3

Anticipated displacement 66 cm

Remarks:



WELL # 84-1B

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST
	INITIAL WATER LEVEL							
1	0:00	321.5	0		7	2:30	322.5	.5
2	0:08	347	25.5		8	3:27	322.5	.5
3	0:21	324	2.5	DEPTH TO WATER INCREASES	9	4:10	322.5	.5
4	0:30	322.5	1			RETEST		
5	0:38	322	.5			0:10	355.5	13.5
6	0:47	322	.5			0:17	327	5
7	1:05	322	.5			0:24	323.5	1.5
8	1:34	322	1			0:36	322	0
9	2:32	322.5	1			1:07	322	0
10	2:49	322.5	1			2:07	322	0
11	4:00	322.5	1			REMOVING SLUG		
12	5:41	323	1.5			0:00	322	0
13	5:54	323	1.5			0:12	325	3
14	6:30	322.5	1			0:24	324	2
15	8:11	322	.5			0:34	323	1
	REMOVING SLUG					0:40	322.5	.5
1	0:11	322.5	.5			0:53	322.5	.5
2	0:25	324	2			1:22	322.5	.5
3	0:33	323.5	1.5			2:09	322.5	.5
4	0:37	322.5	.5			3:57	322.5	.5
5	1:00	322.5	.5			4:45	322.5	.5
6	1:44	322.5	.5					

SITE Western Processing

SLUG TEST FIELD FORM

Date 2/12/85

Investigator J. Doesburg

C. Eddy

M. Lilga

Borehole # 84-2
Dames and Moore well-single well, middle of eastern side of site adjacent to fence.

Radius of borehole 10 cm

Radius of casing 5 cm

Depth of well 1524 cm

Length of screen 152 cm

Reference point for water level measurments Top of PVC

Casing

Elevation NA

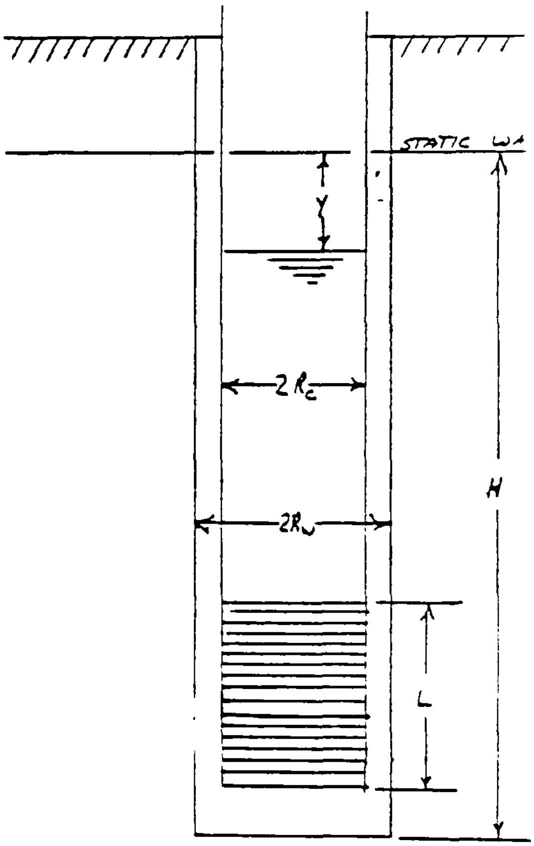
Static water level 266.5 cm

Static water level elevation NA

Ground surface elevation NA

Slug volume 330 cu. in./5408 cm^3

Anticipated displacement 66 cm



Remarks:

WELL # 84-2

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
	INITIAL WATER LEVEL								
1	0:00	266.5	0		23	4:00	249.5	17	
2	0:05	208	58.5		24	4:15	251	15.5	
3	0:15	212.5	54		25	4:30	252.5	14	
4	0:25	215.5	51		26	4:45	253.5	13	
5	0:35	218.5	48		27	5:00	255.5	11	
6	0:45	220.5	46		28	5:20	255.5	11	
7	0:55	222.5	44		29	5:45	257	9.5	
8	1:05	225	41.5		30	6:05	257.5	9	
9	1:15	227	39.5		31	6:30	259	7.5	
10	1:25	229	37.5		32	7:00	260	6.5	
11	1:35	231.5	35		33	7:30	261	5.5	
12	1:45	232.5	34		34	8:00	261.5	5	
13	1:55	235	31.5		35	9:00	262.5	4	
14	2:10	237	29.5		36	10:00	263.5	3	
15	2:20	239	27.5		37	11:00	264.5	2	
16	2:30	240.5	26		38	12:00	265	1.5	
17	2:40	242	24.5		39	13:00	265.5	1	
18	2:50	242.5	24		40	14:00	265.6	.9	
19	3:00	244	22.5		41	16:00	266	.5	
20	3:15	245.5	21		42	18:00	266.5	0	
21	3:30	246.5	20						
22	3:45	248.5	18						

WELL # 84-2

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
	REMOVING SLUG				21	5:30	281	14.5	
1	0:20	321.5	55		22	6:00	278.5	12	
2	0:45	319	52.5		23	6:30	277	10.5	
3	1:00	314	47.5		24	7:00	276.5	10	
4	1:10	312	45.5		25	7:30	275	8.5	
5	1:20	310	43.5		26	8:00	274	7.5	
6	1:25	309	42.5		27	9:00	271.5	5	
7	1:35	308	41.5		28	10:00	270.5	4	
8	1:40	306	39.5		29	11:00	269.5	3	
9	1:50	305	38.5		30	12:00	268.5	2	
10	2:00	303	36.5		31	13:00	268	1.5	
11	2:10	302	35.5		32	14:00	267.5	1	
12	2:20	300	33.5		33	15:00	267	.5	
13	2:30	298.5	32		34	16:20	267	.5	
14	2:55	295	28.5		35	17:20	267	.5	
15	3:25	291	24.5						
16	3:45	289.5	23						
17	4:00	287.5	21						
18	4:15	286	19.5						
19	4:30	285	18.5						
20	5:00	283	16.5						

SITE Western Processing

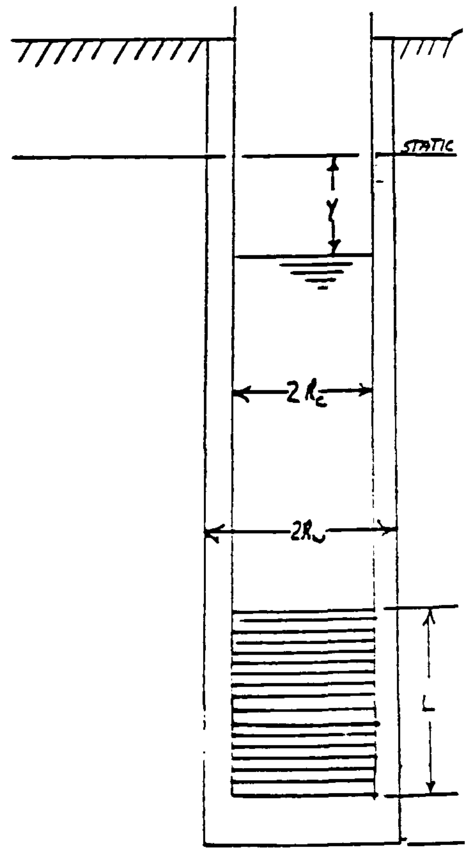
SLUG TEST FIELD FORM

Date 2/12/85

Investigator C. Eddy

M. Lilga

Borehole # 84-3



Radius of borehole 10 cm

Radius of casing 5 cm

Depth of well 1524 cm

Length of screen 152 cm

Reference point for water level measurments Top of PVC

Casing

Elevation NA

Static water level 270 cm

Static water level elevation NA

Ground surface elevation NA

Slug volume 330 cu. in./5408 cm^3

Anticipated displacement 66 cm

Remarks:

WELL # 84-3

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
	INITIAL WATER LEVEL								
1	0:00	270	0		5	1:00	269	-1	
2	0:10	289	19	DEPTH TO	6	1:15	269	-1	
3	0:30	270.5	.5	WATER INCREASES	7	1:30	269	-1	
4	0:55	270	0		8	1:45	269.5	-.5	
5	1:15	270	0		9	2:00	269.5	-.5	
	REMOVING SLUG				10	2:20	270	0	
1	0:13	288	18			REMOVING SLUG			
2	0:25	278	8		1	0:12	285	15	
3	0:35	274	4		2	0:24	277	7	
4	0:45	273	3		3	0:30	275	5	
5	1:00	272	2		4	0:40	273	3	
6	1:15	271.5	1.5		5	0:55	272.5	2.5	
7	1:30	271	1		6	1:05	272	2	
8	1:45	271	1		7	1:20	272	2	
9	2:00	270.5	.5		8	1:40	271	1	
10	2:20	270.5	.5		9	2:00	271	1	
11	2:40	270	0		10	2:20	270.5	.5	
	DROPPING SLUG				11	2:40	270.5	.5	
1	0:20	273	3	DEPTH TO WATER INCR.	12	3:00	270	0	
2	0:30	270	0			DROPPING SLUG			
3	0:40	-269	-1		1	0:08	281	11	DEPTH TO WATER INCR.
4	0:50	268	-2		2	0:21	277	7	

WELL # 84-3

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
3	0:29	271.5	1.5						
4	0:39	270	0						
	REMOVING SLUG								
	0:00	270	0						
1	0:18	276.5	6.5						
2	0:28	274.5	4.5						
3	0:34	274	4						
4	0:41	273	3						
5	0:48	273	3						
6	0:58	272.5	2.5						
7	1:10	271.5	1.5						
8	1:20	271	1						
9	1:30	271	1						
10	1:40	272	2						
11	1:50	271.5	1.5						
12	2:00	271.5	1.5						
13	2:20	271	1						
14	2:40	271	1						
15	3:00	271	1						
16	3:30	270.5	.5						
17	4:00	270.5	.5						

SITE Western Processing

SLUG TEST FIELD FORM

Date 2/12/85

Investigator C. Eddy

M. Lilga

Borehole # 84-4A

Radius of borehole 10 cm

Radius of casing 5 cm

Depth of well 762 cm

Length of screen 152 cm

Reference point for water level measurments Top of PVC

Casing

Elevation NA

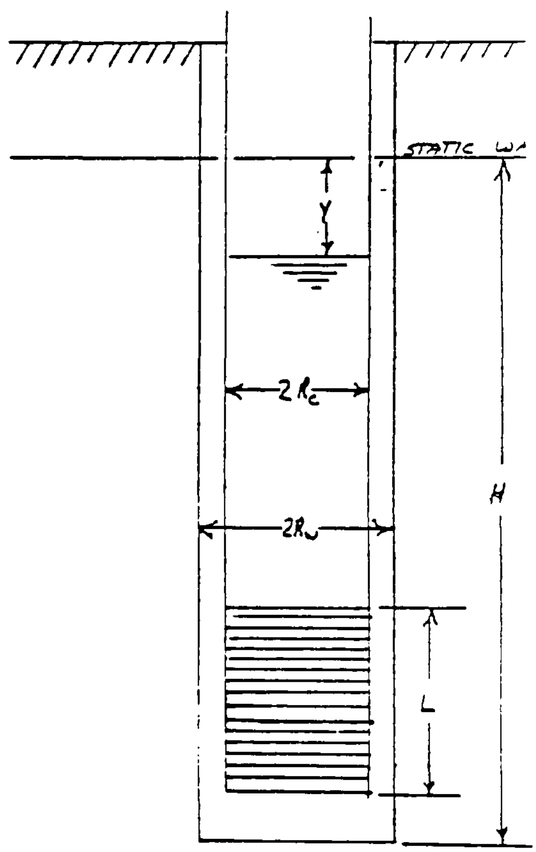
Static water level 268 cm

Static water level elevation NA

Ground surface elevation NA

Slug volume 330 cu. in. /5408 cm^3

Anticipated displacement 66 cm



Remarks:

WELL # 84-4A

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST	#	TIME	DEPTH TO WATER	STATIC MINUS TEST
	INITIAL WATER LEVEL						
1	0:00	268	0				
2	0:10	255	13	8	1:35	269.5	1.5
3	0:20	267	1	9	1:50	269.5	1.5
4	0:35	268	0	10	2:00	269	1
5	1:00	266	2	11	2:15	269	1
6	1:15	266	2	12	2:30	269	1
7	1:35	266.5	1.5	13	3:00	269	1
8	1:45	267	1	14	3:30	269	1
9	1:55	267	1	15	4:15	268.5	.5
10	2:05	267	1	16	5:00	268	0
11	2:15	267	1		DROPPING SLUG		
12	2:30	267	1	1	0:30	263.5	4.5
13	2:45	267	1	2	0:40	263	5
14	3:30	267	1	3	0:50	264.5	3.5
	REMOVING SLUG			4	1:00	265	3
1	0:22	287	19	5	1:10	265.5	2.5
2	0:35	277.5	9.5	6	1:20	265.5	2.5
3	0:46	274	6	7	1:40	266	2
4	0:55	273	5	8	1:50	267	1
5	1:05	271.5	3.5	9	2:05	267.5	.5
6	1:15	270.5	2.5	10	2:25	267.5	.5
7	1:25	270	2	11	3:00	267	1

WELL # 84-4A

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
12	3:30	267.5	.5						
13	4:00	268	0						
	REMOVING SLUG								
	0:00	268	0						
1	1:05	274	6						
2	1:20	269	1						
3	1:45	269.5	1.5						
4	2:00	269	1						
5	2:15	269	1						
6	2:35	268	0						

SITE Western Processing

SLUG TEST FIELD FORM

Date 2/12/85

Investigator C. Eddy

M. Lilga

Borehole # 84-4B

Radius of borehole 10 cm

Radius of casing 5 cm

Depth of well 1524 cm

Length of screen 152 cm

Reference point for water level measurments Top of PVC Casing

Elevation NA

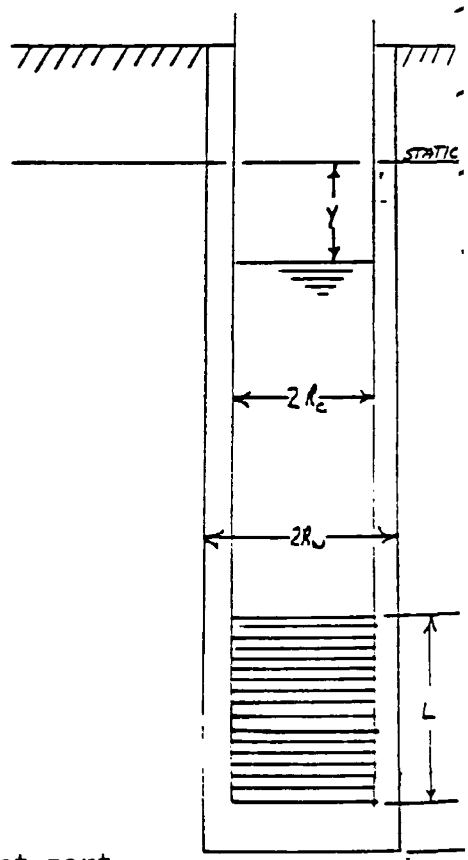
Static water level 269 cm

Static water level elevation NA

Ground surface elevation NA

Slug volume 330 cu. in./5408 cm^3

Anticipated displacement 66 cm



Remarks: "Fizzing" noise noted in well during first part of slug test.

WELL # 84-4B

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
	INITIAL WATER LEVEL								
1	0:00	269	0		23	6:00	224	45	
2	0:08	205	64		24	6:20	225	44	
3	0:20	208	61		25	6:40	225.5	43.5	
4	0:35	209	60		26	7:00	226	43	
5	0:45	210	59		27	7:30	227	42	
6	0:55	211	58		28	8:00	228.5	40.5	
7	1:10	212	57		29	8:35	228.5	40.5	
8	1:25	212	57		30	9:00	230	39	
9	1:40	213	56		31	9:45	231	38	
10	1:50	213.5	55.5		32	10:30	232	37	
11	2:00	213.5	55.5		33	11:15	233	36	
12	2:15	214.5	54.5		34	12:00	234.5	34.5	
13	2:30	215	54		35	13:00	236	33	
14	2:45	215	54		36	14:10	237.5	31.5	
15	3:00	216.5	52.5		37	15:15	239	30	
16	3:30	217.5	51.8		38	16:30	240.5	28.5	
17	3:50	218.5	50.5		39	18:00	242.5	26.5	
18	4:15	220	49		40	19:30	245	24	
19	4:40	221	48		41	21:00	246	23	
20	5:00	221.5	47.5		42	23:00	248	21	
21	5:20	222	47		43	25:00	249	20	
22	5:40	223	46		44	27:45	251	18	

WELL # 84-4B

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
45	30:05	252.5	16.5		67	2:35	310	41	
46	33:00	255	14		68	2:50	308.5	39.5	
47	36:00	256	13		69	3:00	307.5	38.5	
48	40:00	258	11		70	3:15	306	37	
49	45:00	260	9		71	3:30	304	35	
50	50:00	261.5	7.5		72	3:45	303	34	
51	1:00:00	264	5		73	4:00	301.5	32.5	
52	1:10:00	266.5	2.5		74	4:20	300	31	
53	1:20:00	268	1		75	4:40	298	29	
	REMOVING SLUG				76	5:00	296	27	
54 55	0:00 0:10	269 327	0 58		77	5:30	294	25	
56	0:15	328	59		78	6:00	292	23	
57	0:30	326	57		79	6:30	290	21	
58	0:40	324	55		80	7:00	289	20	
59	0:50	323	54		81	8:00	285.5	16.5	
60	1:00	321.5	52.5		82	9:00	282	13	
61	1:10	320	51		83	10:00	280	11	
62	1:20	319.5	50.5		84	11:00	278	9	
63	1:35	317	48		85	12:00	277	8	
64	1:45	316	47		86	14:00	274.5	5.5	
65	2:00	314.5	45.5		87	16:00	272.5	3.5	
66	2:20	310.5	41.5		88	18:00	271.5	2.5	

WELL # 84-4B

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
89	20:00	270	1						
90	22:00	270	1						
91	25:20	270	1						
92	28:00	270	1						
93	32:00	270	1						
	33 minutes is 3:49 p.m.								
94	1:10:00	271	at 4:26 p.m.						

SITE Western Processing

SLUG TEST FIELD FORM

Date 2/12/85

Investigator C. Eddy

M. Lilga

Borehole # 84-5A

Radius of borehole 10 cm

Radius of casing 5 cm

Depth of well 762 cm

Length of screen 152 cm

Reference point for water level measurments Top of PVC

Casing

Elevation NA

Static water level 241 cm

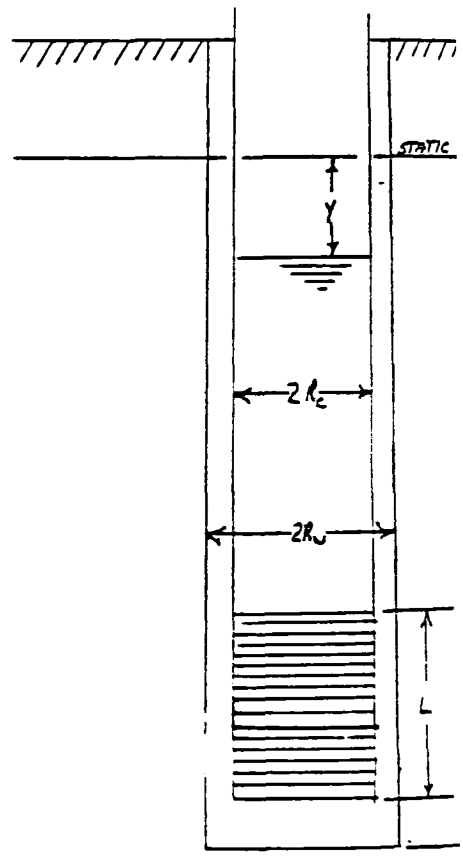
Static water level elevation NA

Ground surface elevation NA

Slug volume 330 cu. in. /5408 cm^3

Anticipated displacement 66 cm

Remarks:



WELL # 84-5A

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
	INITIAL WATER LEVEL								
1	0:00	241	0		23	6:45	220.5	20.5	
2	0:12	201	40		24	7:30	221	20	
3	0:27	197	44		25	8:15	222.5	18.5	
4	0:39	202	39		26	9:00	223	18	
5	0:51	202.5	38.5		27	10:00	225	16	
6	1:05	204	37		28	11:00	227	14	
7	1:15	204.5	36.5		29	12:30	228	13	
8	1:25	205	36		30	14:00	229.5	11.5	
9	1:35	206	35		31	15:30	231.5	9.5	
10	1:45	206.5	34.5		32	17:00	232	9	
11	2:00	207	34		33	18:30	233	8	
12	2:15	208	33		34	20:00	234	7	
13	2:30	209	32		35	22:00	236	5	
14	2:45	210	31		36	24:00	237.5	3.5	
15	3:00	211	30		37	27:00	238	3	
16	3:20	212.5	28.5		38	30:00	239	2	
17	3:40	213	28		39	35:00	241	0	
18	4:00	214	27			REMOVING SLUG			
19	4:30	215	26		1	0:05	303	62	
20	5:00	216	25		2	0:14	301	60	
21	5:30	217	24		3	0:22	300	59	
22	6:00	218	23		4	0:33	297	54	

WELL # 84-5A

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
5	0:44	295	54		27	10:00	254	13	
6	0:50	294	53		28	11:00	253	12	
7	1:10	292	51		29	12:00	251.5	10.5	
8	1:20	290	49		30	13:30	249.5	8.5	
9	1:40	288	47		31	15:00	247	6	
10	1:50	286	45		32	17:00	246	5	
11	2:05	285	44		33	19:00	245	4	
12	2:15	284	43		34	22:00	244	3	
13	2:30	282	41		35	25:00	243	2	
14	2:45	280.5	39.5		37	29:00	242	1	
15	3:00	279	38		38	33:07	241	0	
16	3:20	277	36						
17	3:40	275	34						
18	4:00	273.5	32.5						
19	4:30	271.5	30.5						
20	5:00	269.5	28.5						
21	5:30	267.5	26.5						
22	6:00	265.5	24.5						
23	6:45	262.5	21.5						
24	7:30	260	19						
25	8:15	259	18						
26	9:02	257	16						

SITE Western Processing

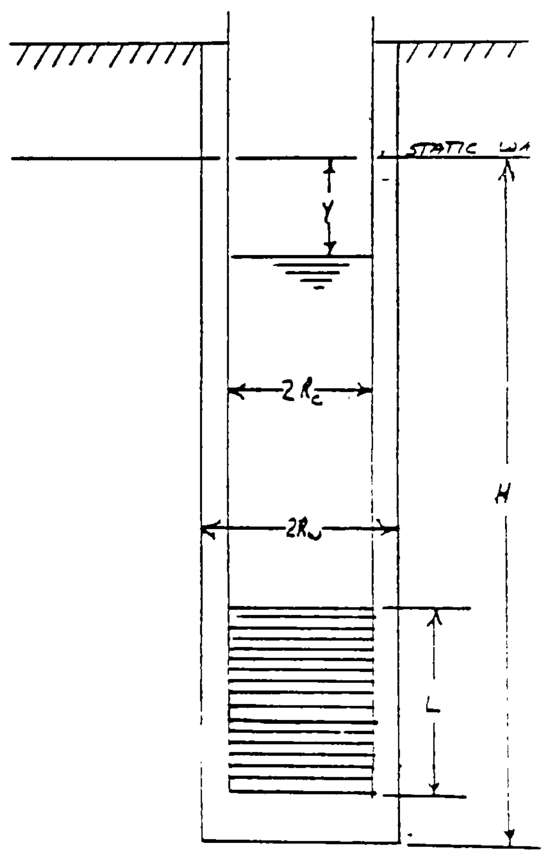
SLUG TEST FIELD FORM

Date 2/13/85

Investigator C. Eddy

M. Lilga

Borehole # 84-5B



Radius of borehole 10 cm

Radius of casing 5 cm

Depth of well 1524 cm

Length of screen 152 cm

Reference point for water level measurments Top of PVC

Casing

Elevation NA

Static water level 259.5 cm

Static water level elevation NA

Ground surface elevation NA

Slug volume 330 cu. in. /5408 cm^3

Anticipated displacement 66 cm

Remarks:

WELL # 84-5B

SLUG TEST FIELD FORM

#	TIME	DEPTH TO WATER	STATIC MINUS TEST		#	TIME	DEPTH TO WATER	STATIC MINUS TEST	
	WATER LEVEL INCREASES					DROPPING SLUG			
1	0:00	259.5	0						
2	0:16	263.5	4		1	0:02	256	3.5	
3	0:25	259.5			2	0:12	277	17.5	
4	0:35	259	-.5		3	0:19	261	1.5	
5	0:49	259	-.5		4	0:27	260	.5	
6	1:-5	259.5	0		5	0:33	259.5	0	
	REMOVING SLUG				6	0:41	259.5	0	
1	0:09	259	.5			REMOVING SLUG			
2	0:20	259.5	0		1	0:12	260	.5	
3	0:50	259.5	0		2	0:22	259.5	0	
	DROPPING SLUG				3	0:30	259.5	0	
1	0:10	306	464.5		4	0:36	259.5	0	
2	0:18	262	3.5	WATER LEVEL INCREASES	5	0:45	259.5	0	
3	0:30	259.5	0		6	0:53	259.5	0	
4	0:45	259.5	0		7	1:02	259.5	0	
5	1:01	259.5	0						
	REMOVING SLUG								
1	0:12	261	1.5						
2	0:19	260	.5						
3	0:25	259.5	0						
4	0:35	259.5	0						
5	1:10	259.5	0						

APPENDIX B

PLOTS USED TO CALCULATE HYDRAULIC CONDUCTIVITY FROM SLUG TESTS

For the EPA Wells:

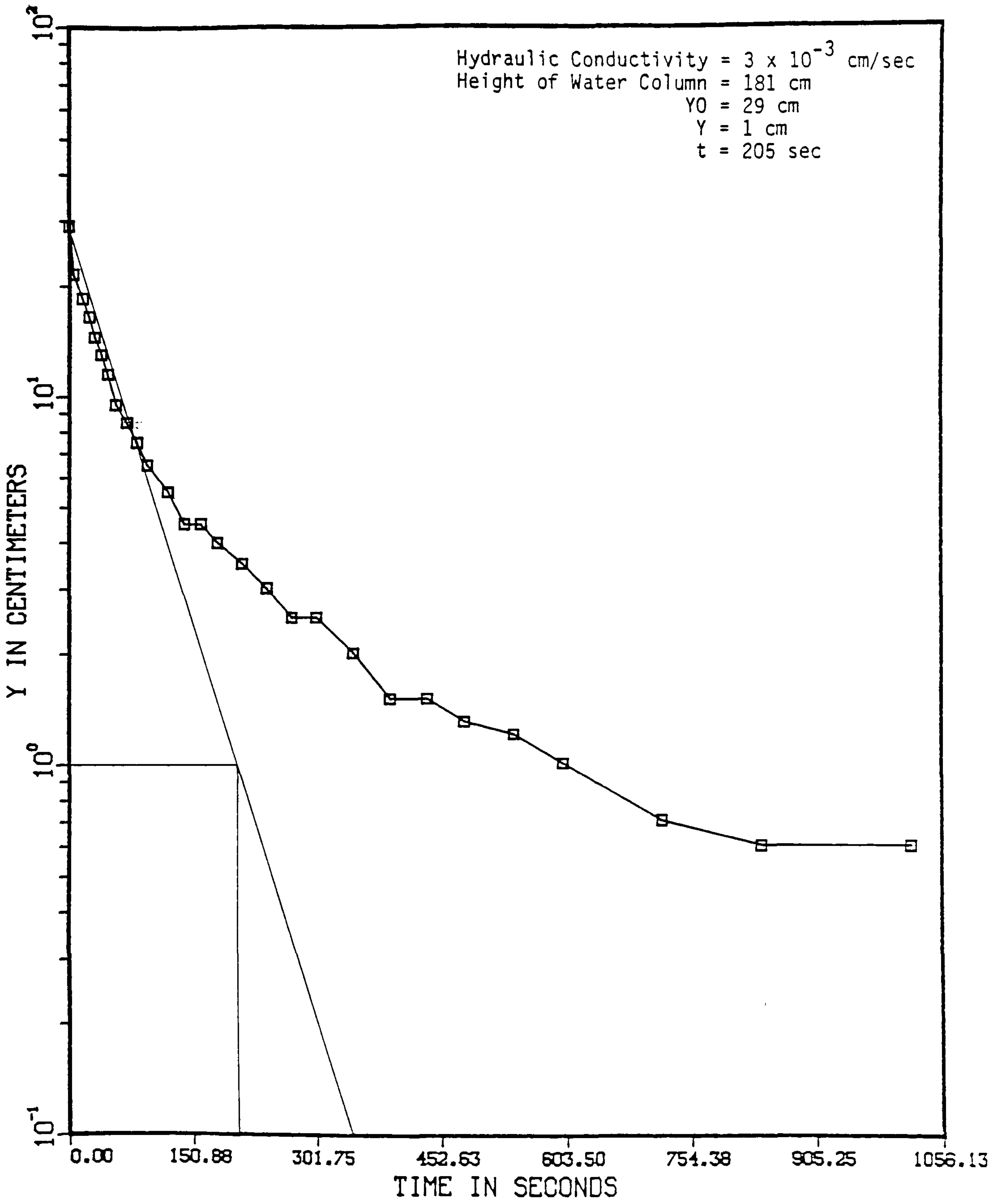
Length of Screen = 91 cm
Borehole Radius = 10 cm
Well Radius = 5 cm
A* = 1.8
B* = 0.2

For the Dames and Moore Wells:

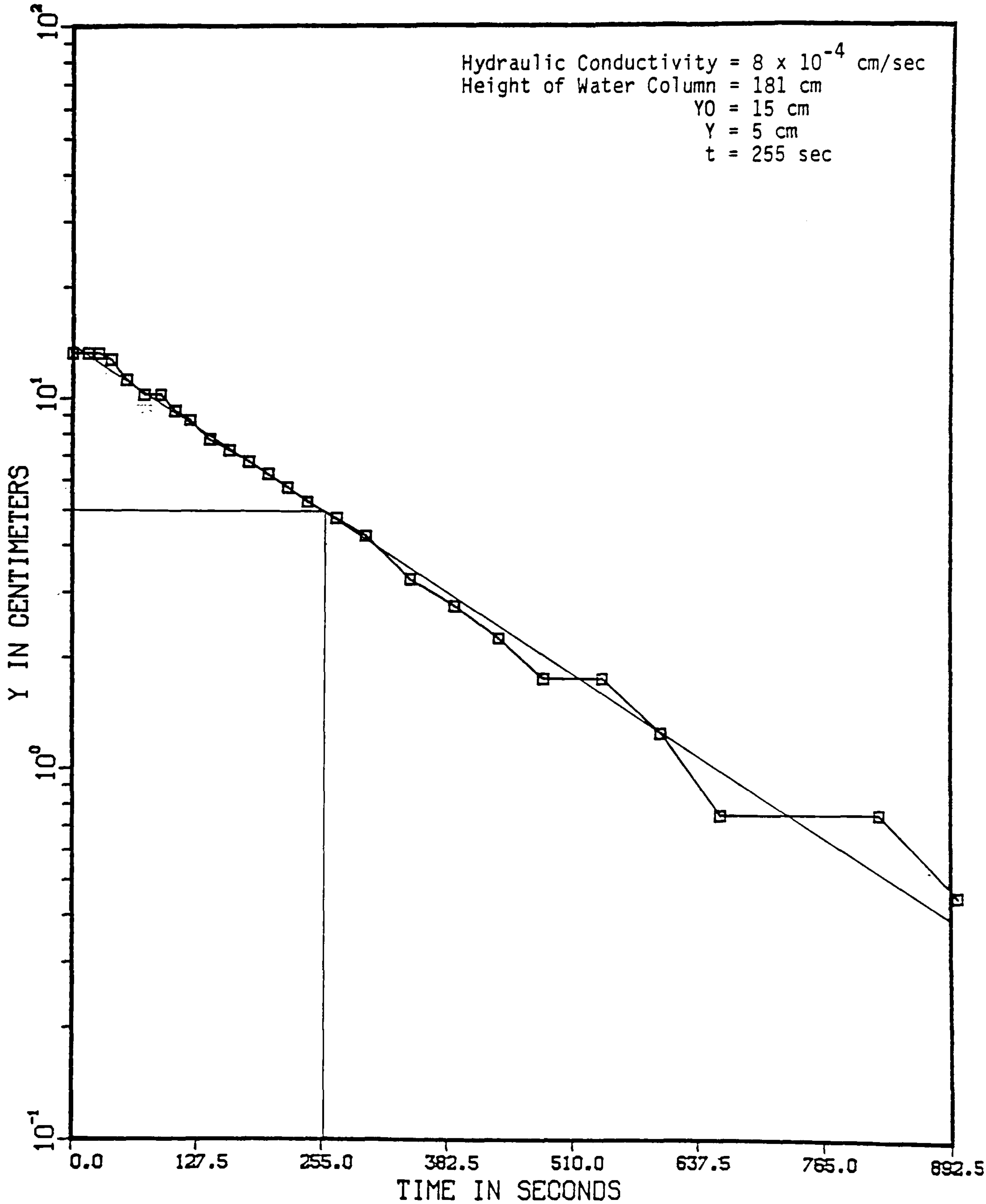
Length of Screen = 152 cm
Borehole Radius = 10 cm
Well Radius = 5 cm
A* = 2.0
B* = 0.2

From Bouwer and Rice (1976).

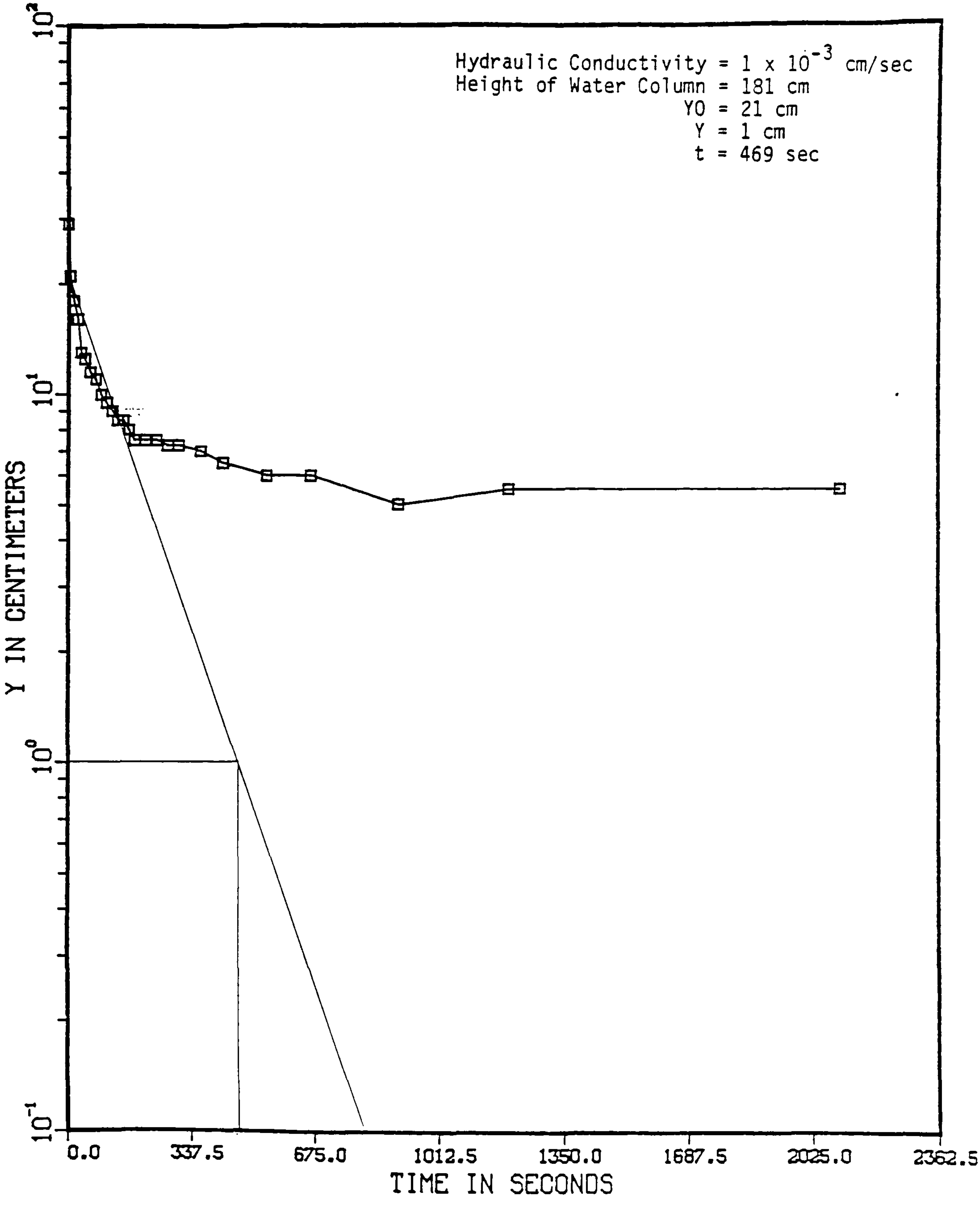
WELL 1A -- DROPPING SLUG (1)



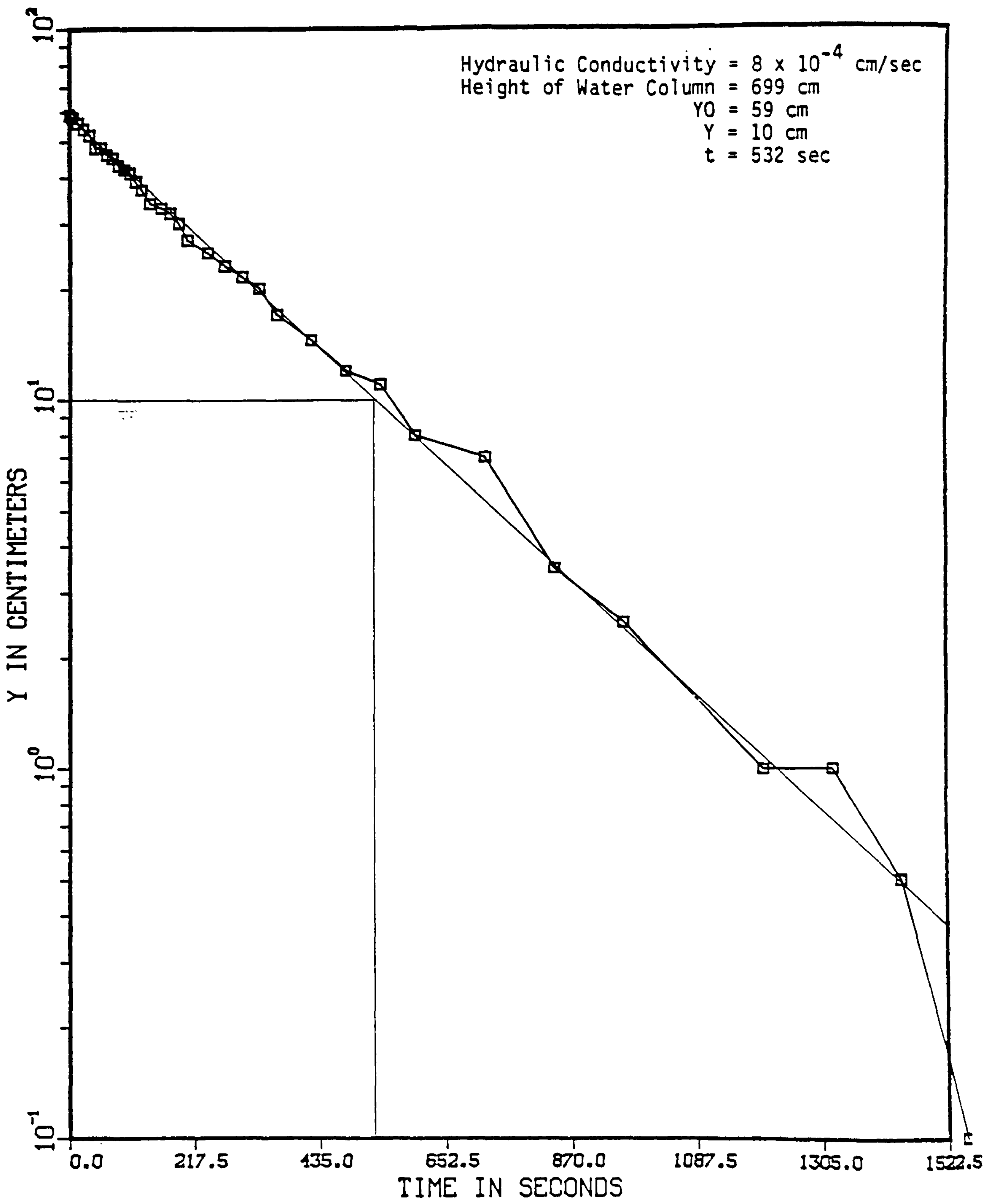
WELL 1A -- REMOVING SLUG (1)



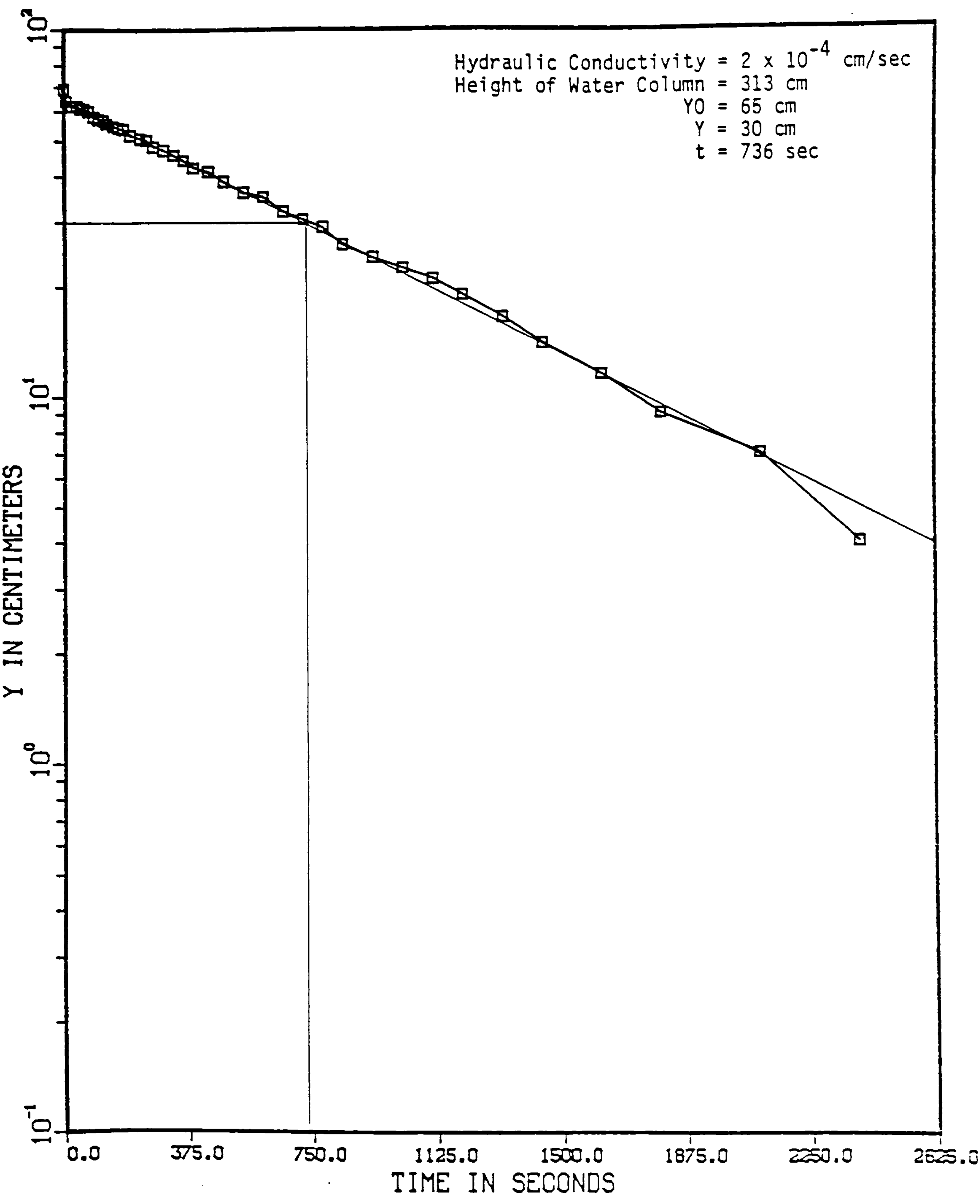
WELL 1A -- DROPPING SLUG (2)



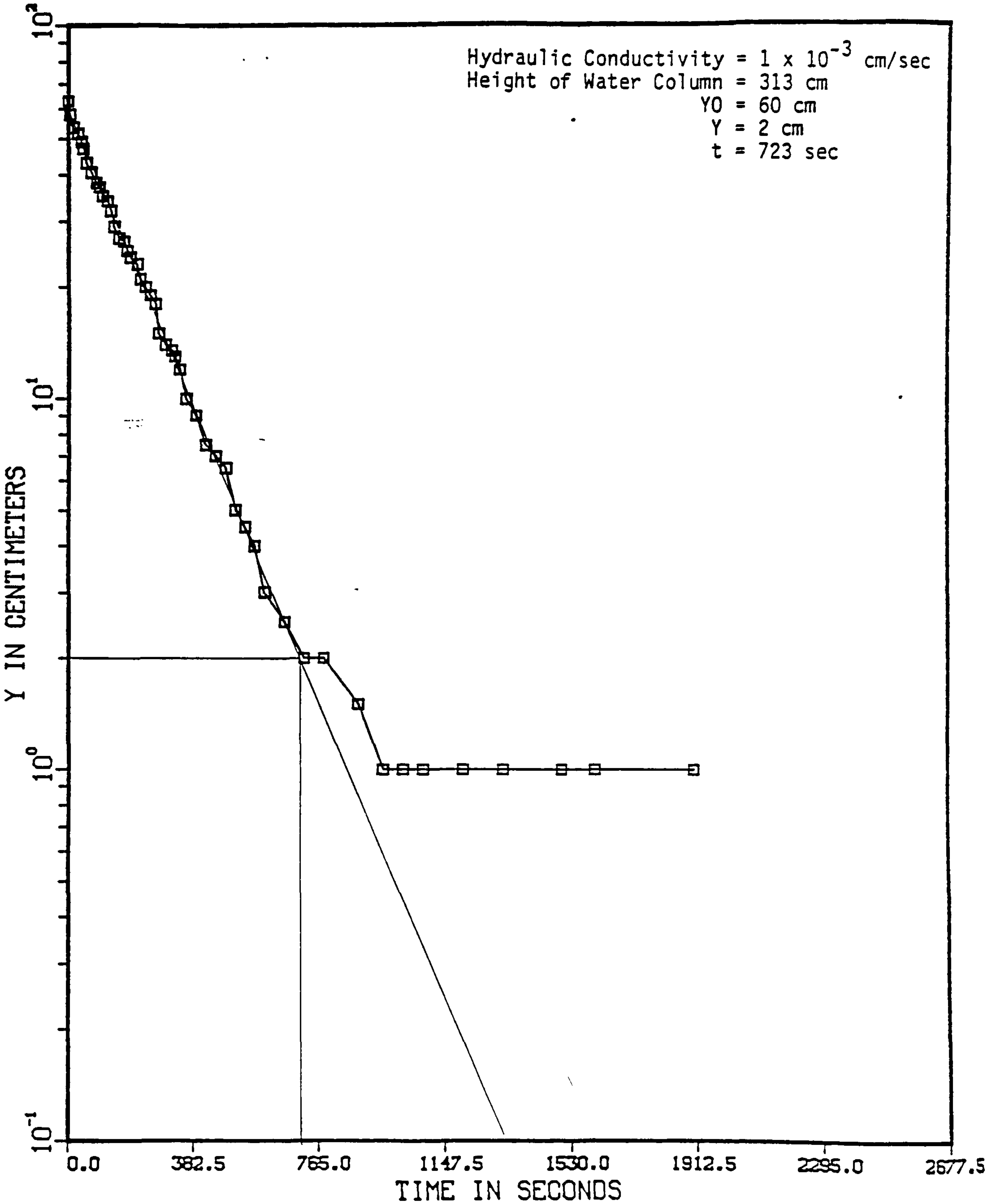
WELL 1B -- DROPPING SLUG (1)

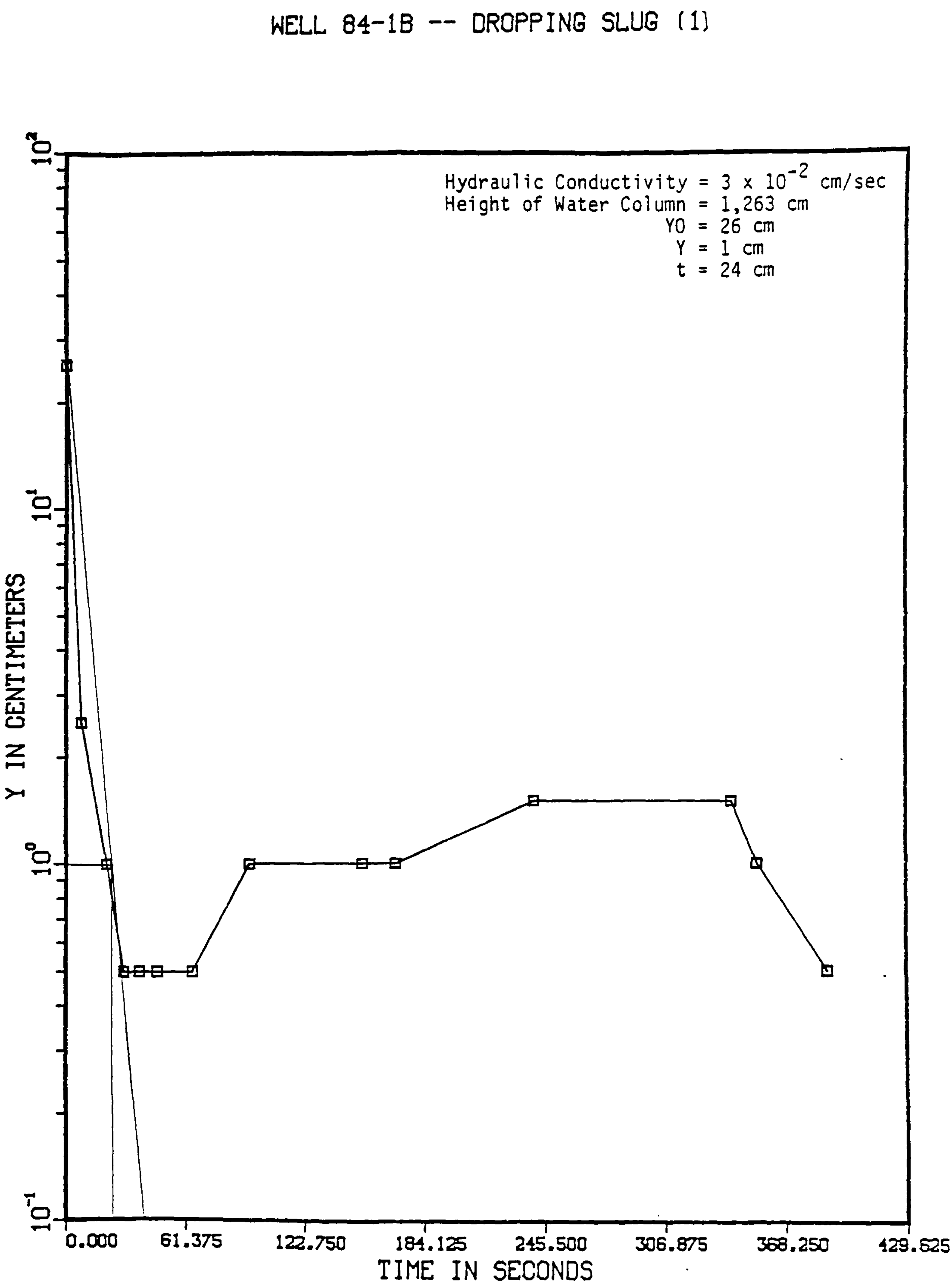


WELL 17A -- REMOVING SLUG (1)

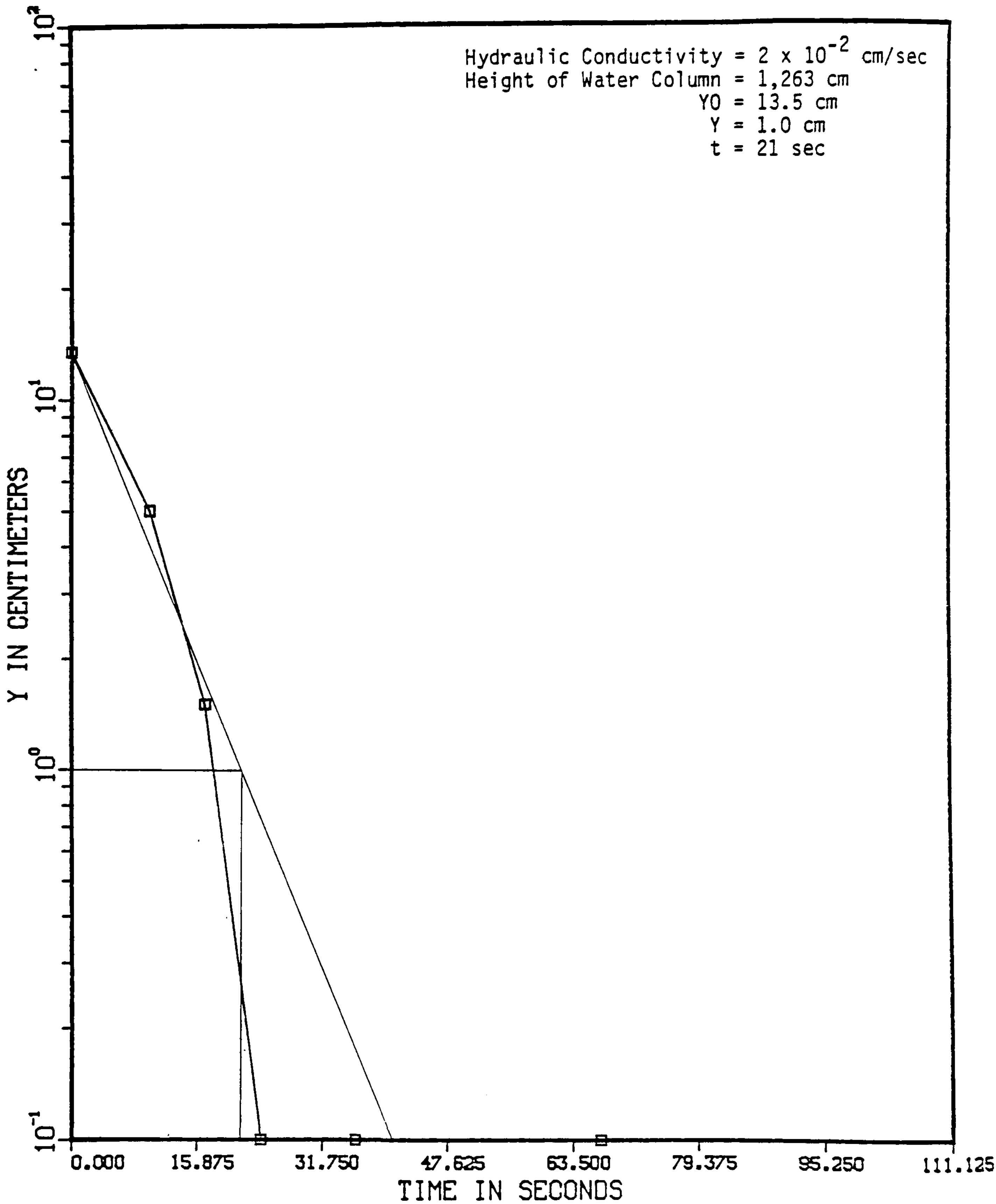


WELL 17A -- DROPPING SLUG (1)

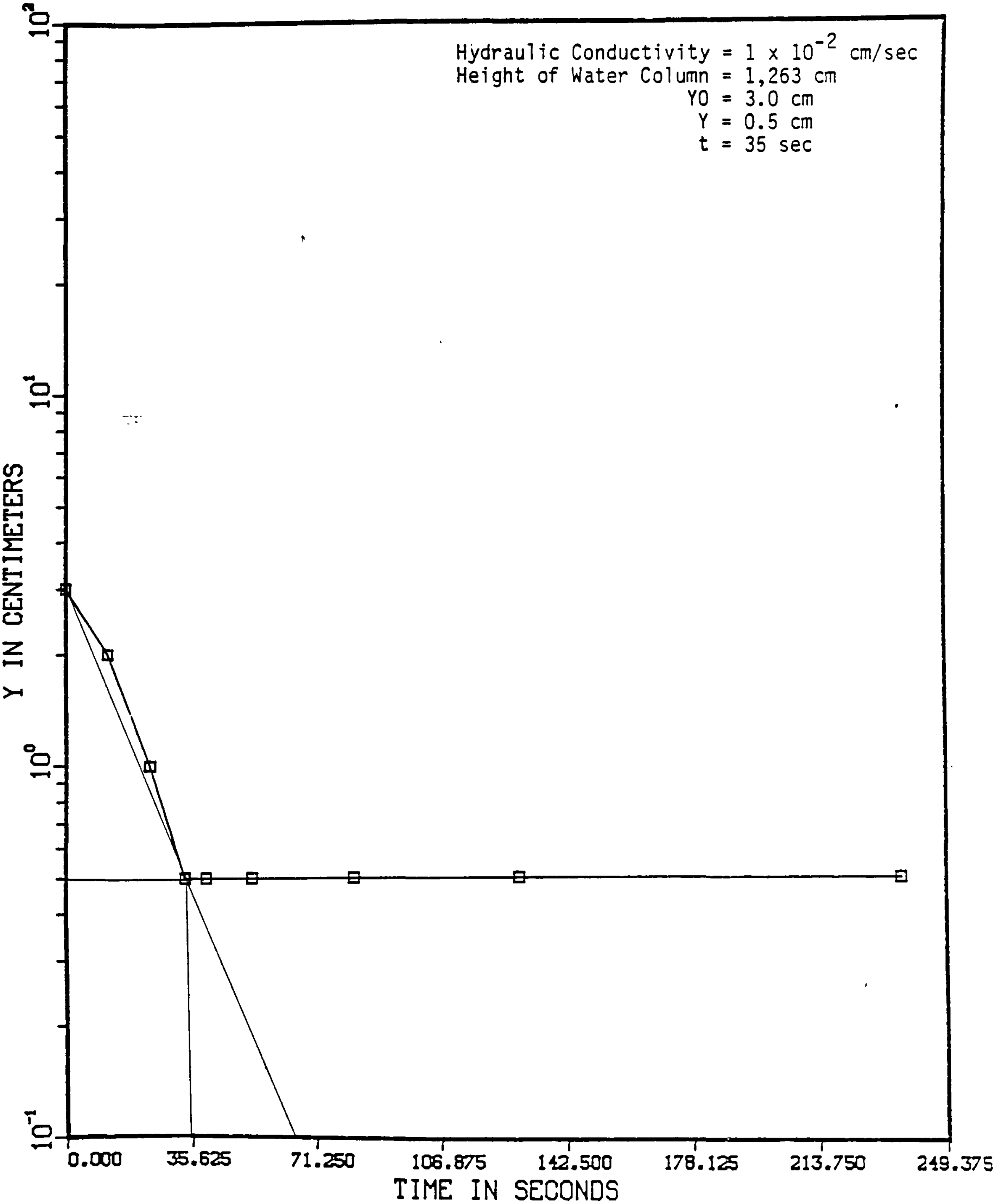



WELL 84-1B -- DROPPING SLUG (1)
Hydraulic Conductivity = 3 x 10-2 cm/sec
Height of Water Column = 1,263 cm
YO = 26 cm
Y = 1 cm
t = 24 cm
Y IN CENTIMETERS
10^2
10^1
10^0
10^-1
0.000
61.375
122.750
184.125
245.500
306.875
368.250
429.625
TIME IN SECONDS

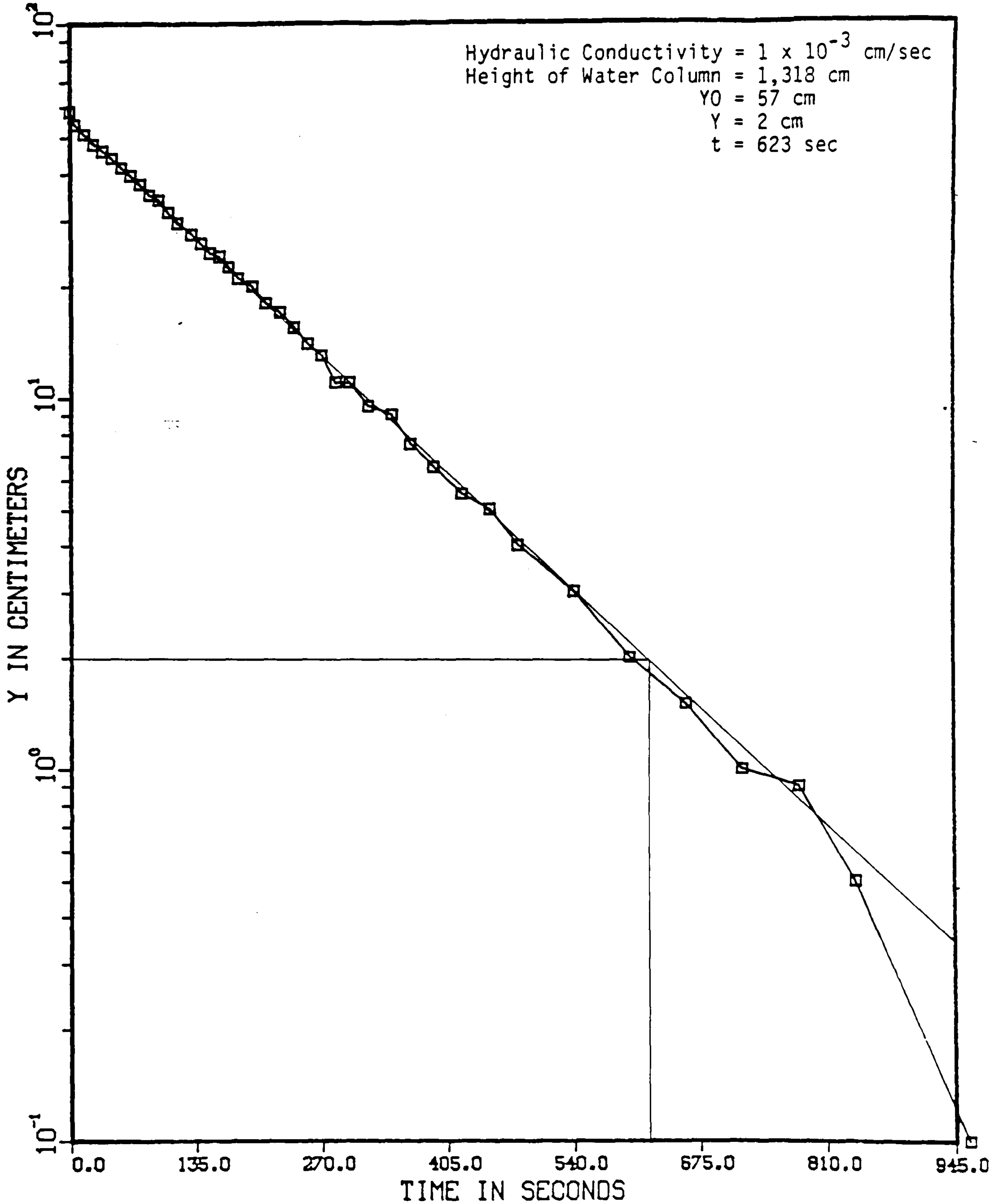
WELL 84-1B -- DROPPING SLUG (2)



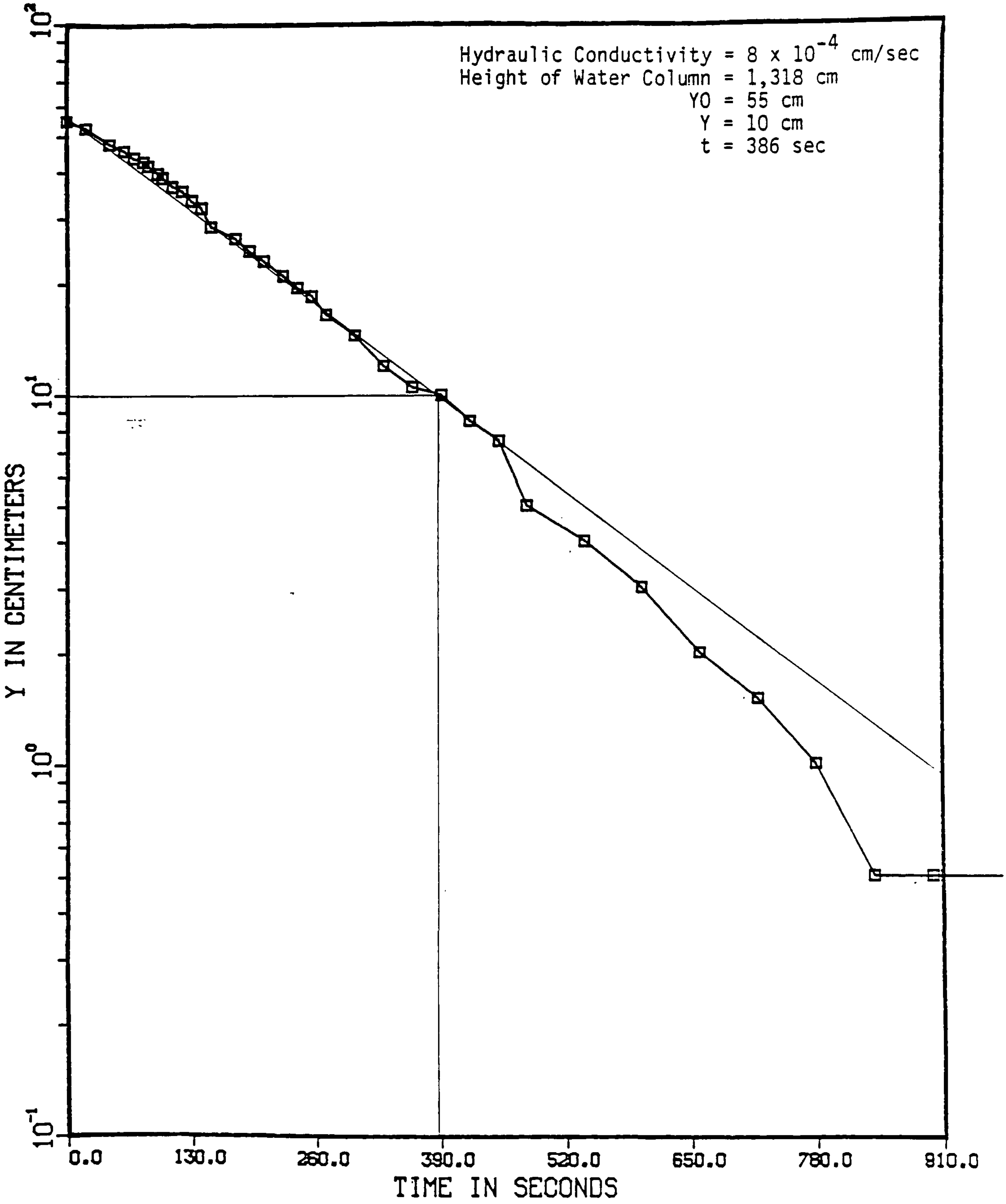
WELL 84-1B -- REMOVING SLUG (2)



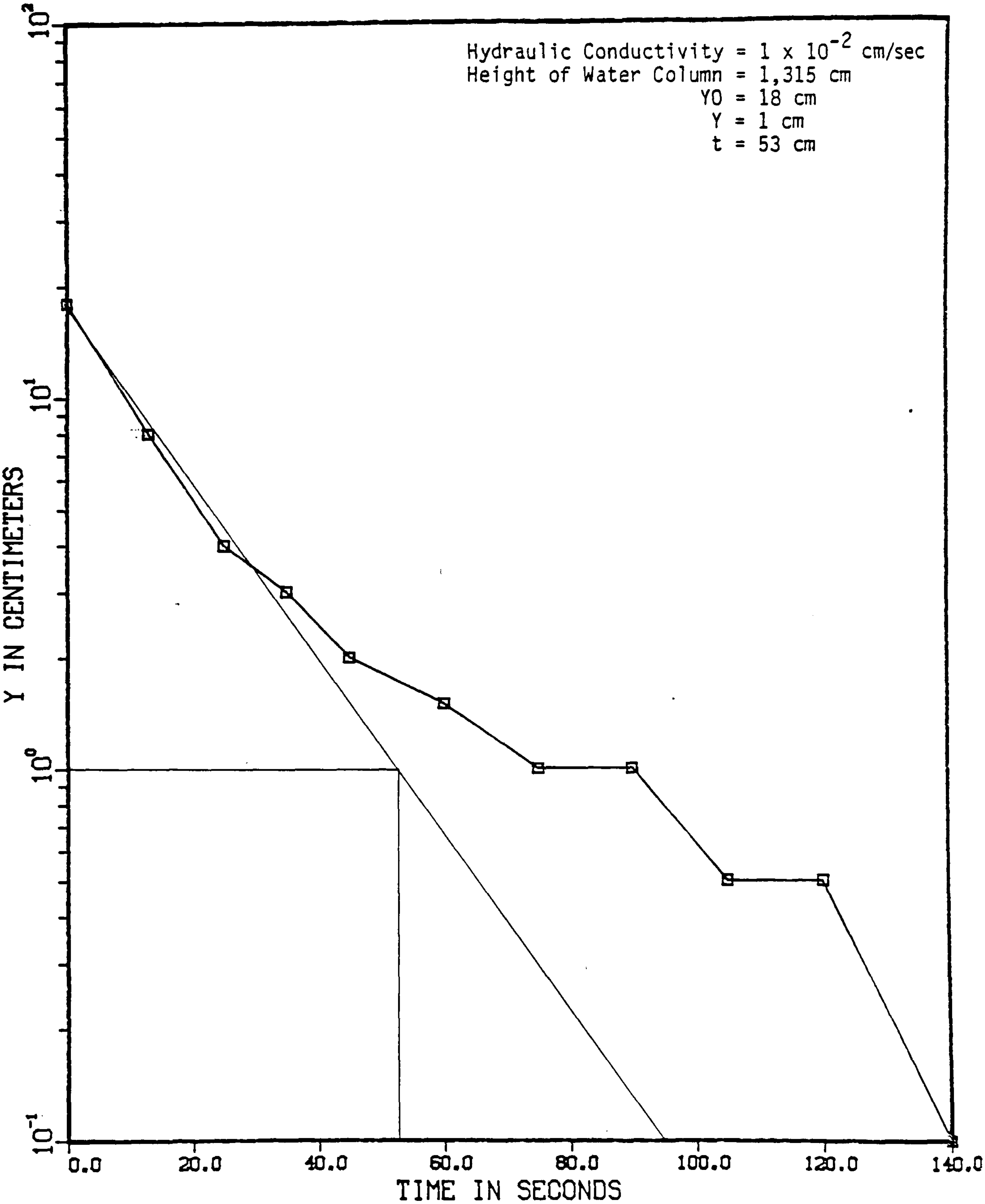
WELL 84-2 -- DROPPING SLUG (1)



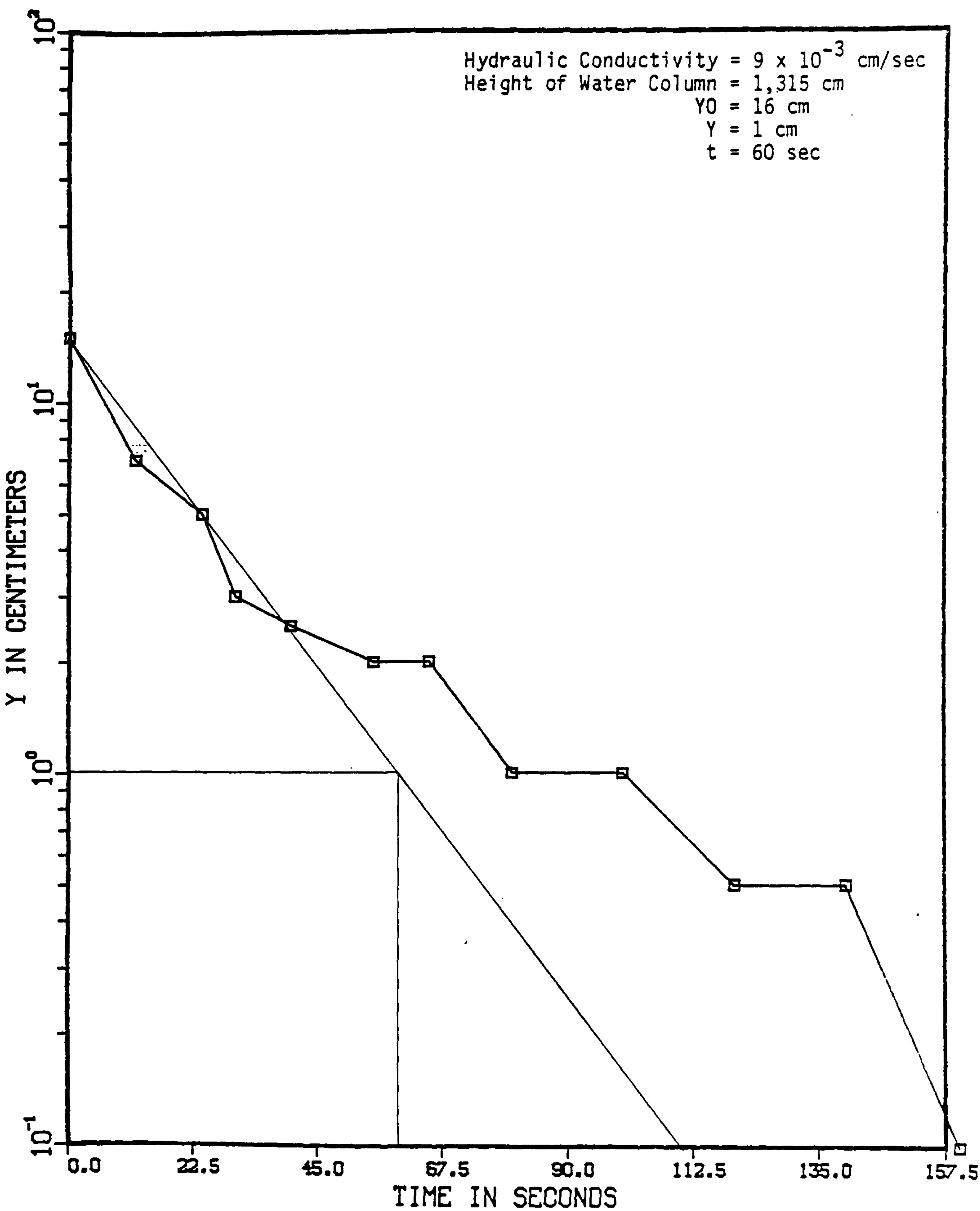
WELL 84-2 -- REMOVING SLUG (1)



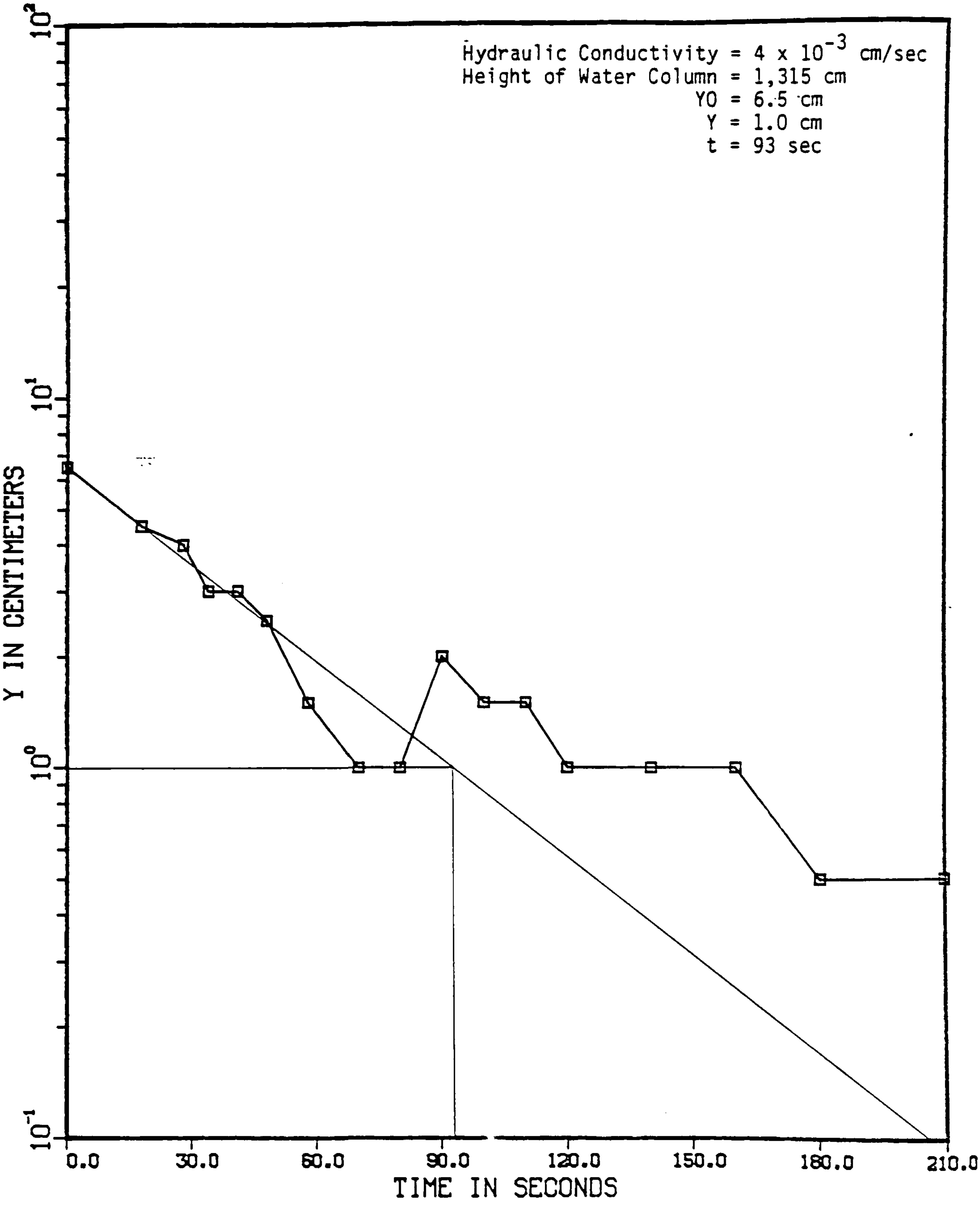
WELL 84-3 -- REMOVING SLUG (1)



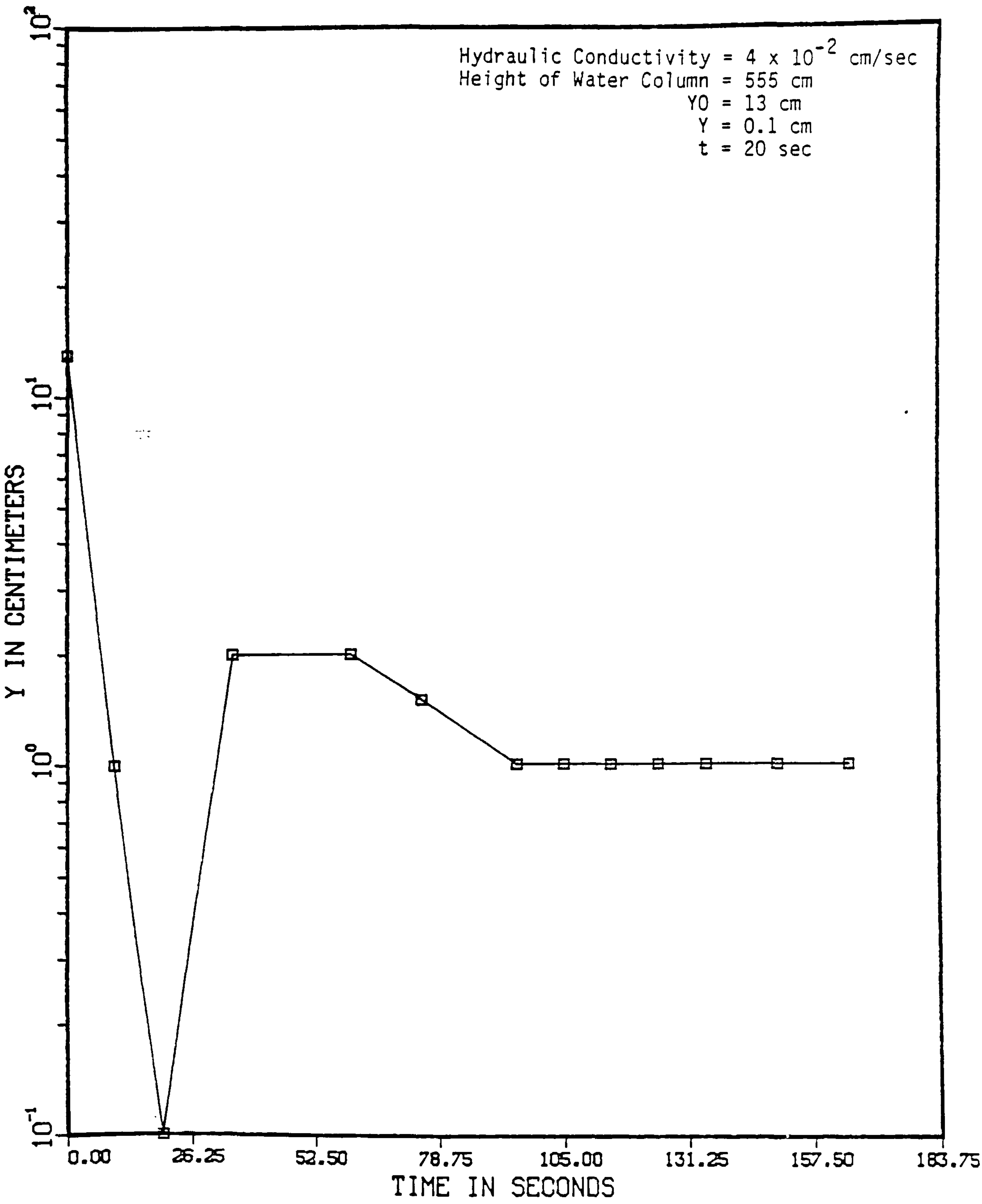
WELL 84-3 -- REMOVING SLUG (2)



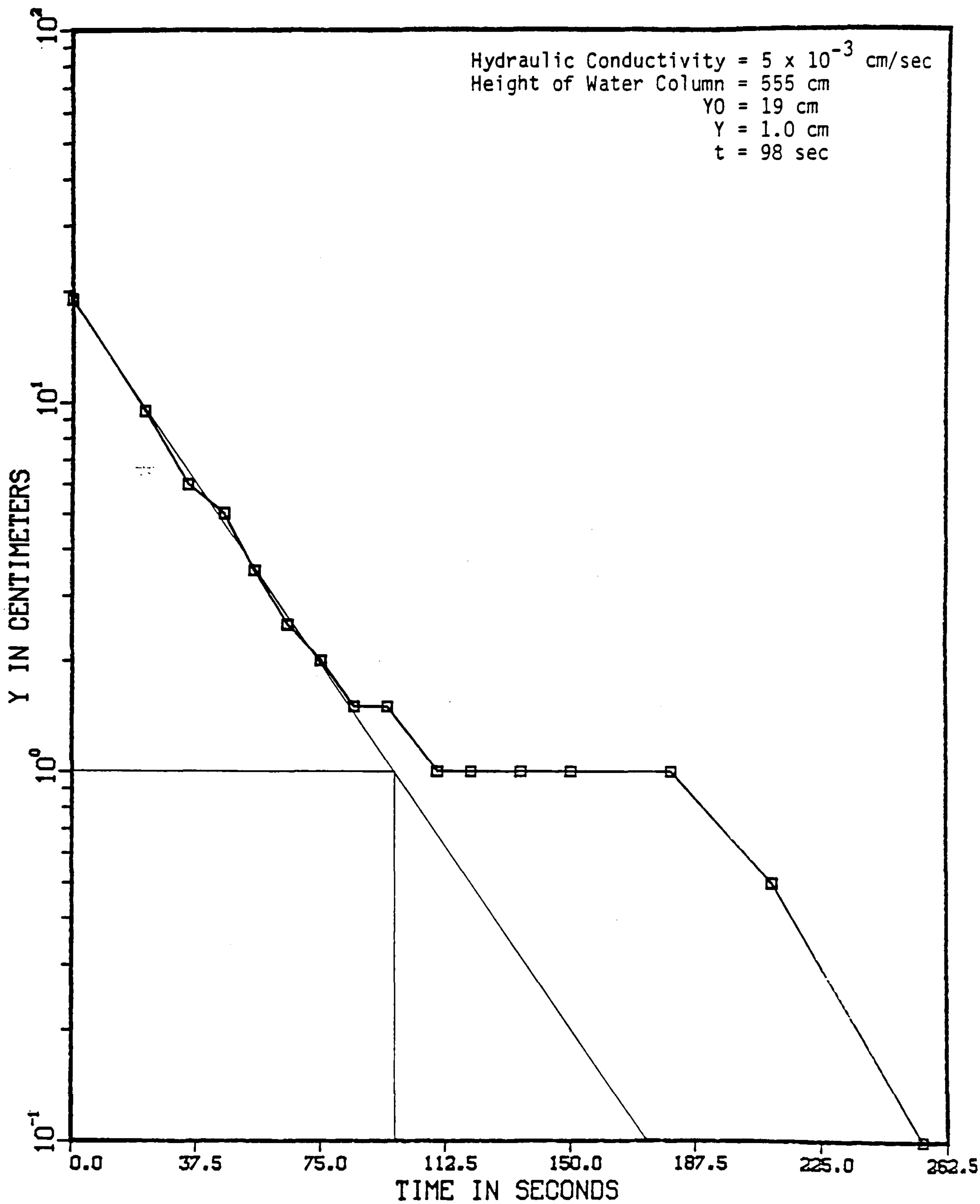
WELL 84-3 -- REMOVING SLUG (3)



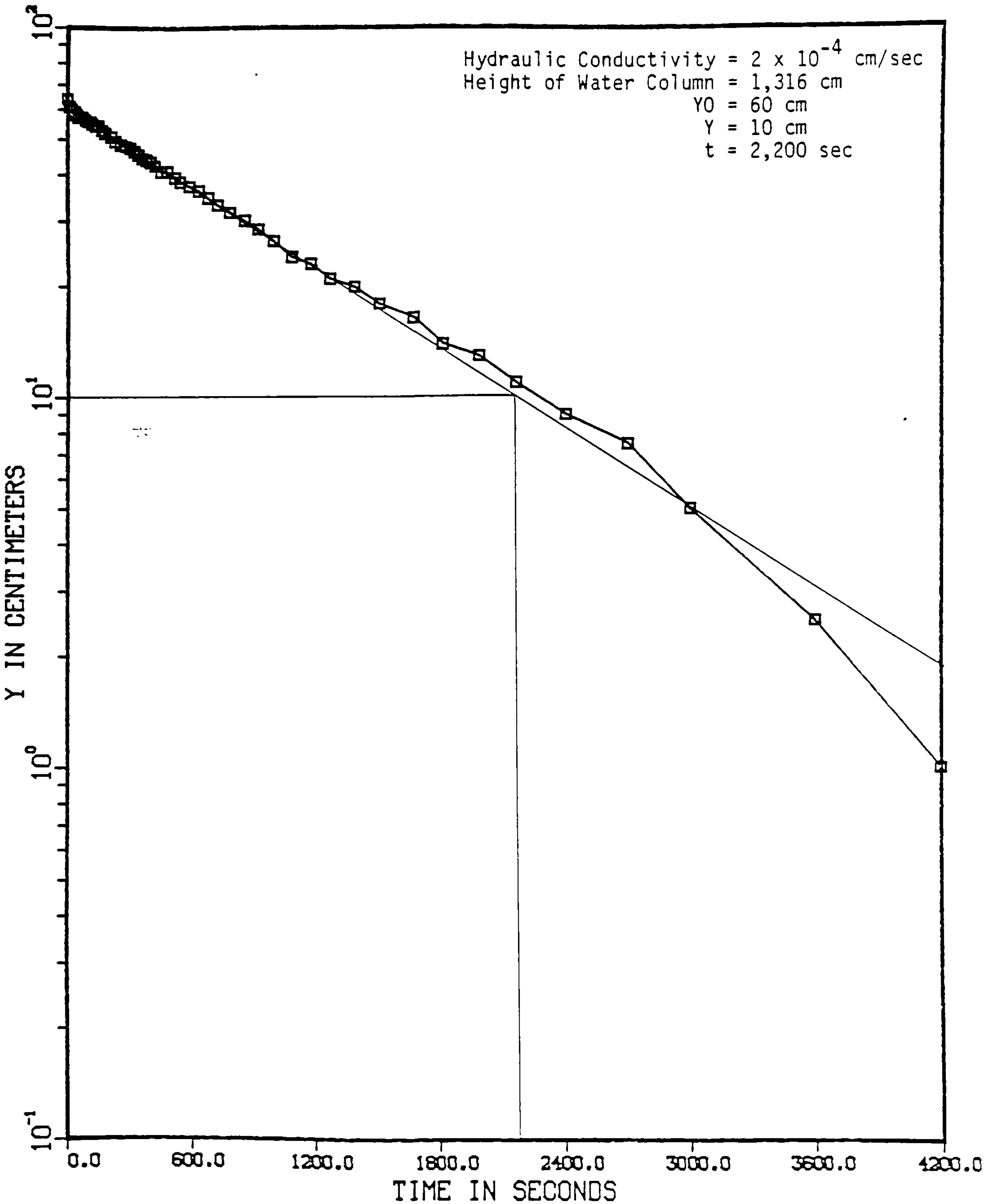
WELL 84-4A -- DROPPING SLUG (1)



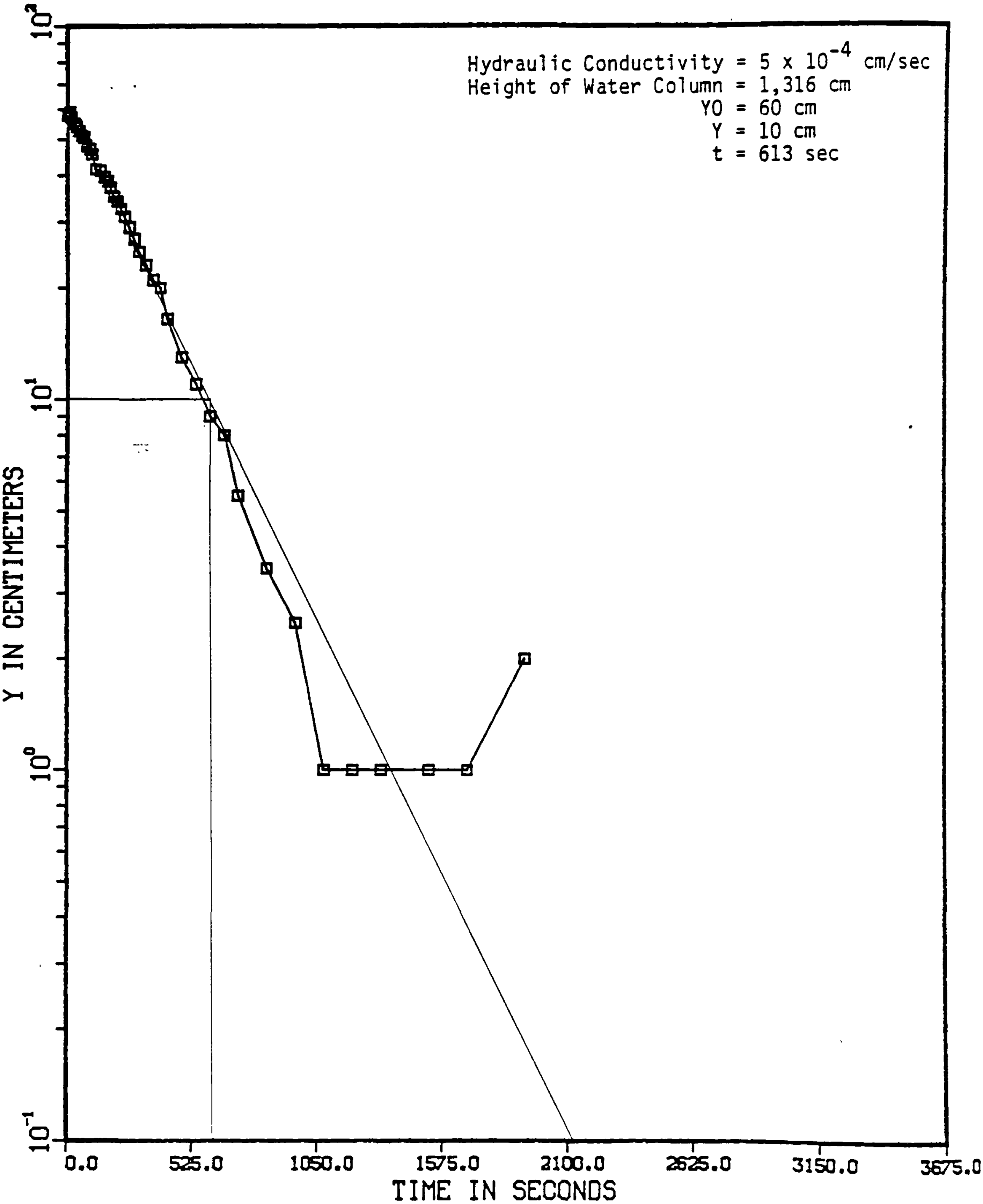
WELL 84-4A -- REMOVING SLUG (1)



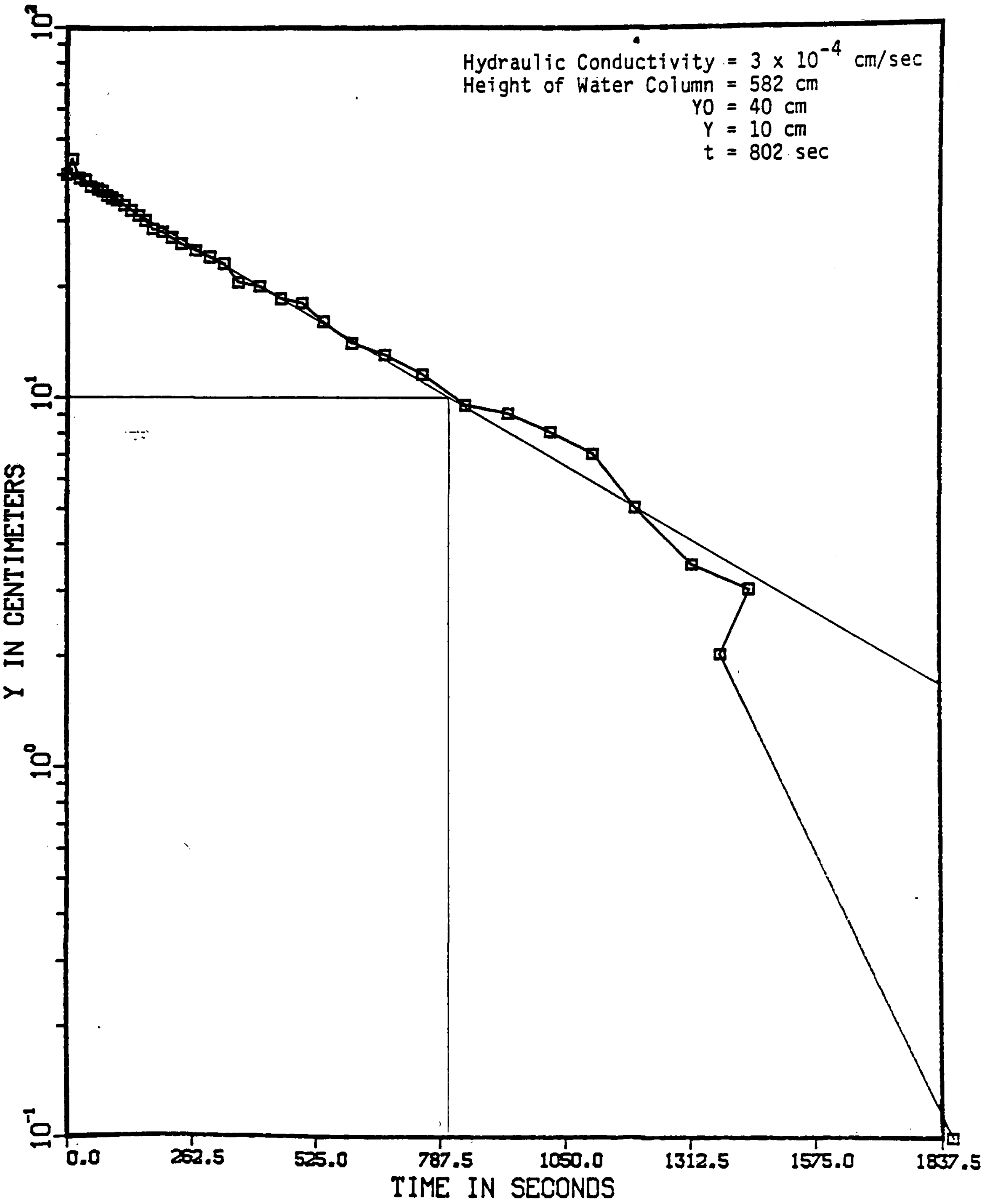
WELL 84-4B -- DROPPING SLUG (1)



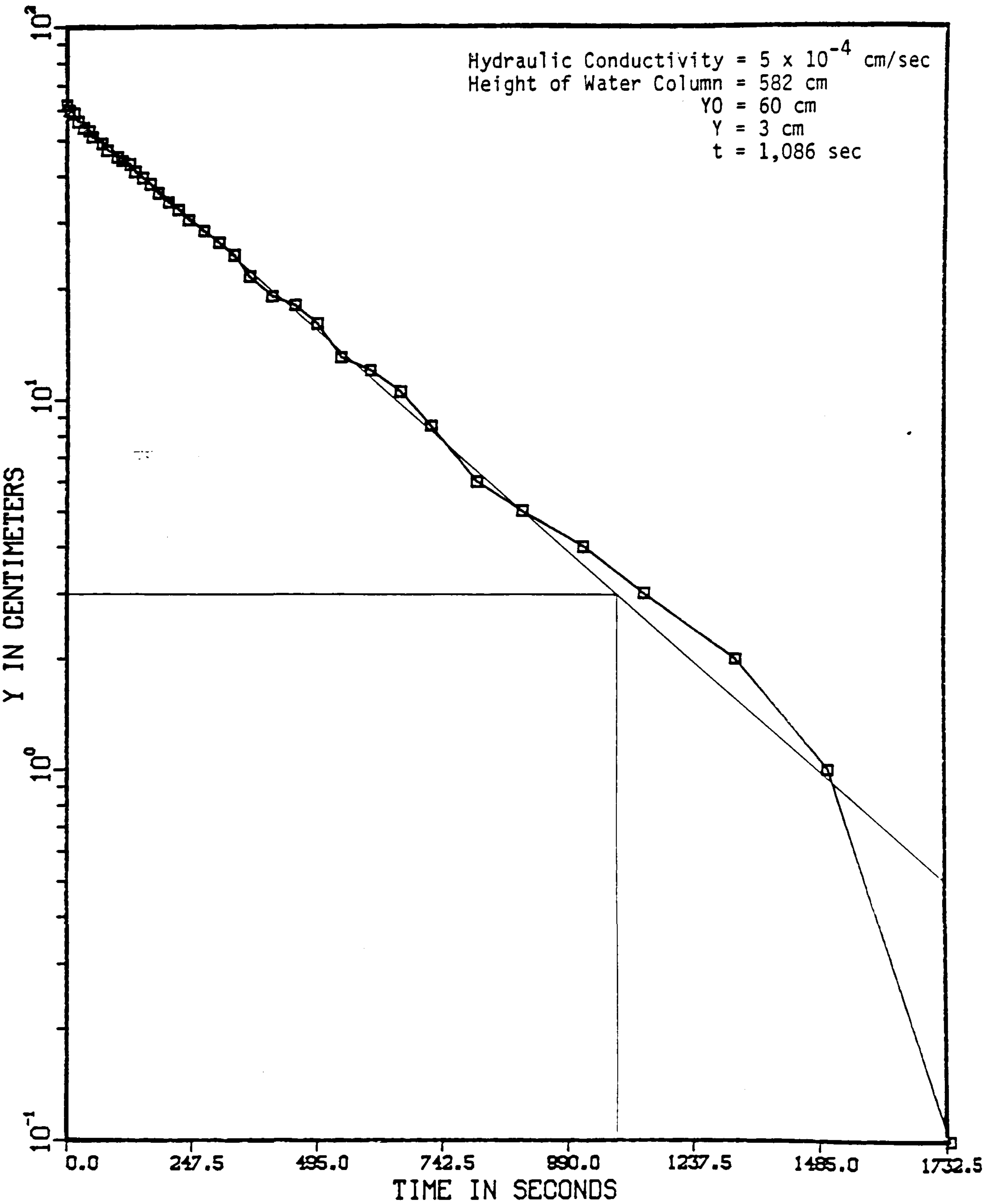
WELL 84-4B -- REMOVING SLUG (1)

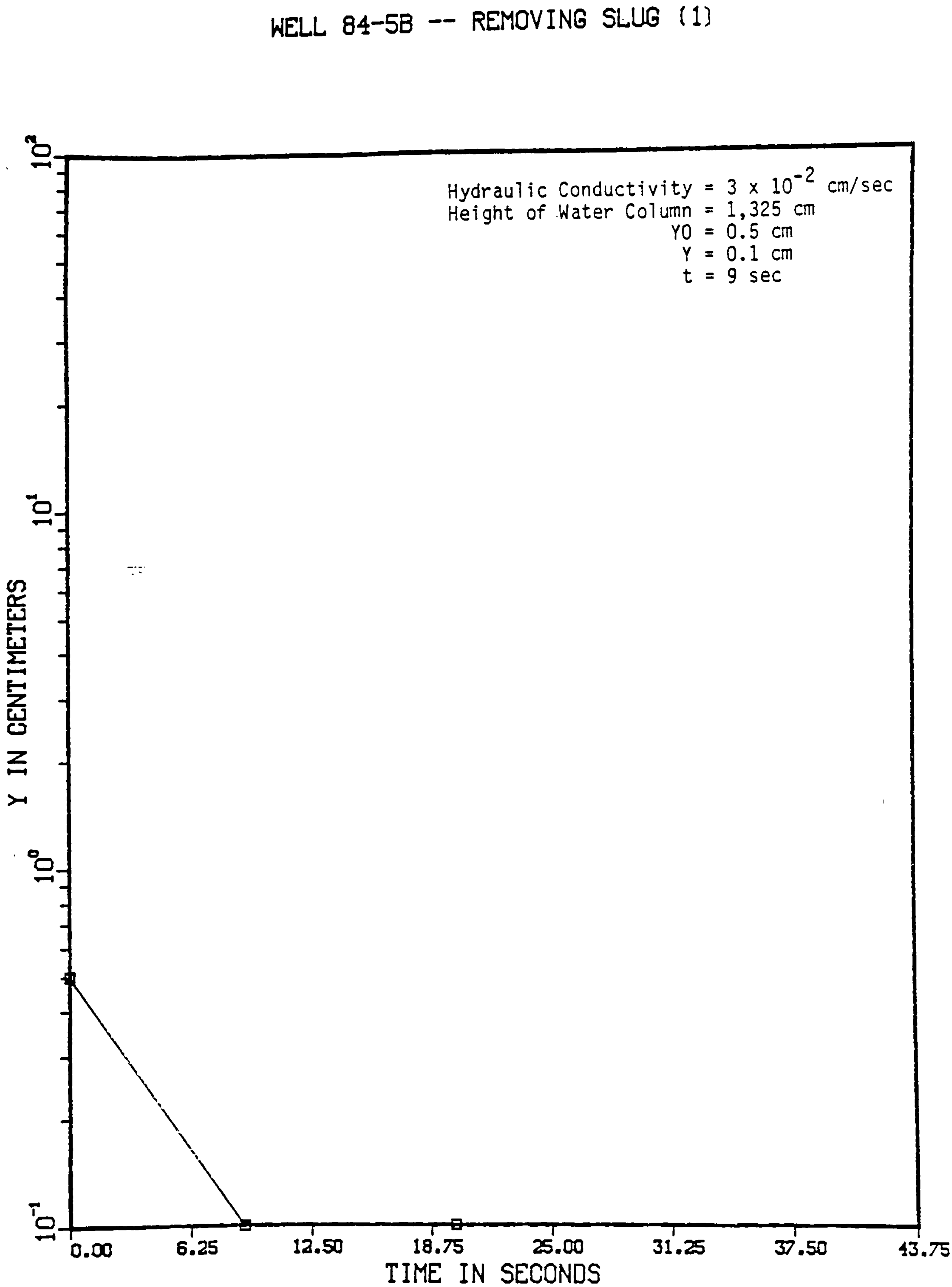


WELL 84-5A -- DROPPING SLUG (1)

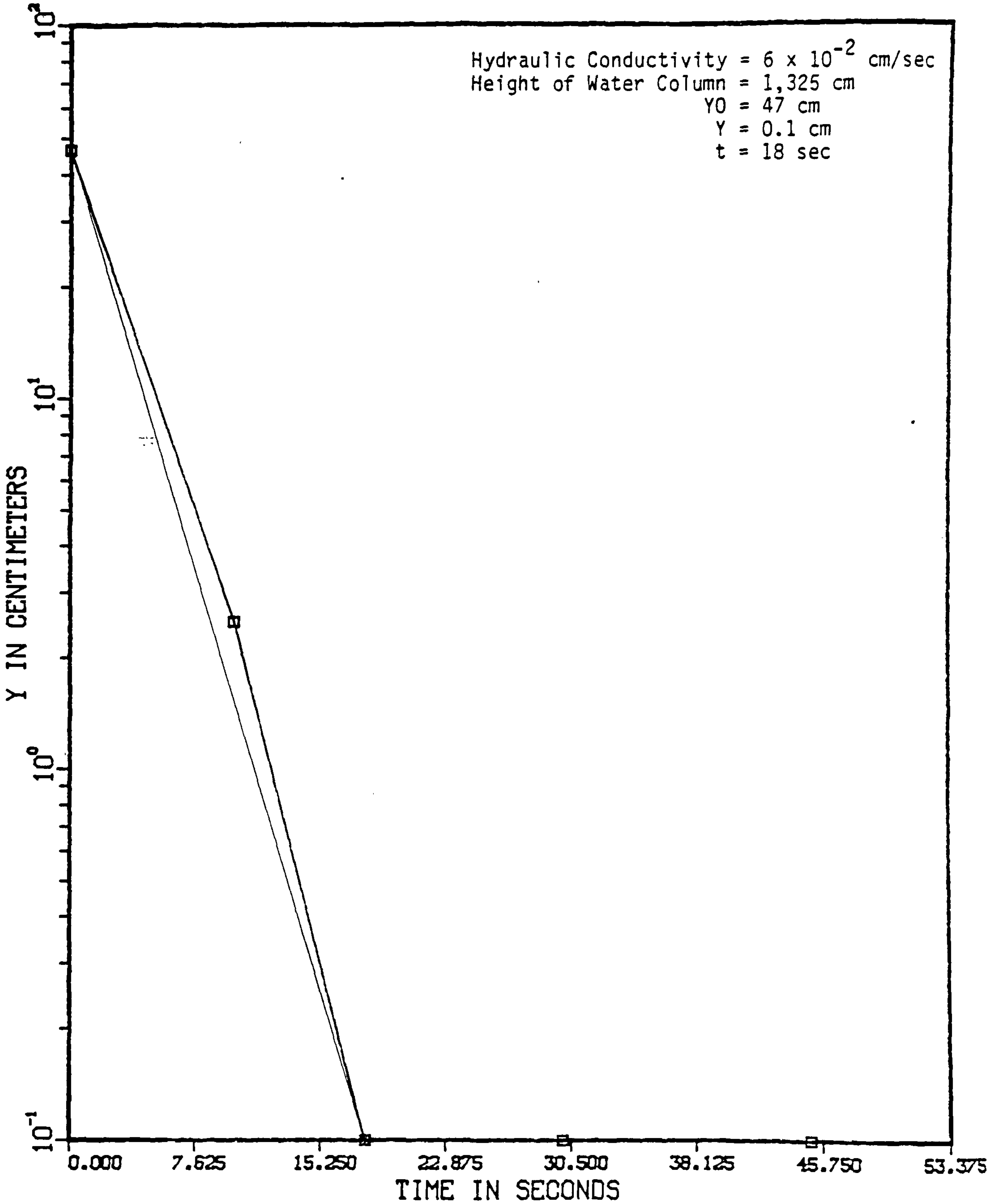


WELL 84-5A -- REMOVING SLUG (1)




WELL 84-5B -- REMOVING SLUG (1)
Hydraulic Conductivity = 3 x 10^-2 cm/sec
Height of Water Column = 1,325 cm
Y0 = 0.5 cm
Y = 0.1 cm
t = 9 sec
Y IN CENTIMETERS
10^2
10^1
10^0
10^-1
0.00
6.25
12.50
18.75
25.00
31.25
37.50
43.75
TIME IN SECONDS

WELL 84-5B -- DROPPING SLUG (2)



APPENDIX D

CALCULATION OF LEACH DURATION AND AMOUNT FROM SOURCE AREAS

Three sources of TCE have been identified at the Western Processing Site based on the concentration levels measured in the soil and water. These three sources are: Reaction Pond I; Reaction Pond III; and the area around Well 21. A known disposal site is not located in the vacinity of Well 21, but the high concentrations of TCE in soil and water samples from Well 21 indicate that disposal occurred in this area. Calculations were made to estimate the mass of TCE present in the unsaturated zone (both in soil and water) of these three locations based on 1982 soil concentration measurements (EPA, 1982). These mass estimates were then used to estimate the time required for TCE to completely leach out of the unsaturated zone into the saturated zone. Time of leach calculations were based on the average annual recharge at the site (8 in./yr - Appendix A). The results of these caluclations were used to determine the number of years past 1982 to keep the sources active in the model, and to estimate the source strength for each time step simulated.

SOURCE AREA DATA

The data used to estimate the mass of TCE in the unsaturated zone of each source area are summarized below.

Reaction Pond I

The total volume of contaminated unsaturated soil at Reaction Pond I was estimated to be 46,250 ft^3. This number is based on a surface area of 9,250 ft^2 and an average depth of unsaturated contaminated soil of 5 ft. The surface area is the actual area associated with Reaction Pond I. The average depth of contaminated soil was estimated from the soil sampling depths and concentrations reported in Table D-1. The TCE concentration in the soil was estimated to be 600,000 ppb based on the measured soil concentrations from Wells 15 and 17 (Table D-1). In order to represent a worst case, the concentration was estimated to be about the maximum observed soil concentration and was assumed to be uniform over the area of the disposal site.

Table D-1. TCE Soil Concentrations Near Reaction Pond I

	Soil Concentration (ppb)	
Depth (ft)	Well 15	Well 17
3	U	U
6	580,000	558,000
9	180,000	350,000

U = Not Detected

Reaction Pond III

The total volume of contaminated unsaturated soil at Reaction Pond III was estimated to be 35,650 ft^3. This number is based on a surface area of 7,125 ft^2 and an average depth of contaminated soil of 5 ft. The surface area is the actual area associated with Reaction Pond III. The average depth of contaminated soil was estimated from the soil sampling depths and concentrations reported in Table D-2. The TCE concentration in the soil was estimated to be 700 ppb based on the measured soil concentrations from Well 20 (Table D-2). In order to represent a worst case, the concentration was estimated to be about the maximum observed soil concentration and was assumed to be uniform over the area of the disposal site.

Table D-2. TCE Soil Concentrations Near Reaction Pond III

	Soil Concentration (ppb)
Depth (ft)	Well 20
3	U
6	M
9	676
12	544

U = Not Detected

M = Present but below minimum quantifiable limit.

Area Around Well 21

The total volume of contaminated unsaturated soil in the area around Well 21 was difficult to estimate because this area is not a known disposal area. Therefore, the volume was assumed to be the same as that of Reaction Pond III, 35,650 ft^3. This volume is based on the same surface area and average depth as those used for Reaction Pond III. The TCE concentration in the soil was estimated to be 1,600 ppb based on the measured soil concentration from Well 21 (Table D-3).

Table D-3. TCE Soil Concentrations Near Well 21 Source

	Soil Concentration (ppb)
Depth (ft)	Well 21
3	U
6	U
9	116
12	1,520

U = Not Detected

CALCULATION OF SOURCE AREA MASS

The calculations of mass in the unsaturated zone for each of the three source locations are presented below.

For all source areas, the actual and effective porosities of the unsaturated material were set at 0.25 and 0.15, respectively. The distribution coefficient (Kd) and retardation factor for sorption of TCE on the unsaturated soils at all source locations were set at 0.2 and 4.0, respectively.

The equation used to calculate the mass of TCE at each source location is:

$$Mass_{TCE} = \{\text{mass in soil}\} + \{\text{mass in water}\}$$
$$= (1 - \Theta_A)(C_s)(Vol_s)(\gamma_s) + (\Theta_E)(C_w)(Vol_s)(\gamma_w) \quad \text{(D-1)}$$

Where:

$Mass_{TCE}$ = total mass of TCE in the soil (lb)

Θ_A = actual water porosity

Θ_E = effective porosity

C_s = TCE concentration (ppb) in the soil

Vol_s = total volume of unsaturated soil (ft^3)

γ_s = density of the soil (lb/ft^3)

C_w = TCE concentration (ppb) in the water $\{C_w = \frac{1}{Kd}(C_s)\}$

γ_w = density of the water (lb/ft^3)

The density of the soil was calculated as:

$$\gamma_s = (1 - \Theta_A)(\gamma) = 121.5 \text{ lb/ft}^3$$

where:

Θ_A = actual porosity (0.25)

γ = dry density of sand (162 lb/ft^3)

The TCE soil concentrations were determined based on measured soil concentrations in the unsaturated zone at wells around the source areas. The TCE water concentrations were estimated to be five times greater than the soil concentrations based on an distribution coefficient (Kd) of 0.2. The ppb notation is equivalent to $lb/10^9$ lb in the total mass calculation.

Reaction Pond I

Based on the data in Table D-4, the total mass of TCE in the unsaturated zone at Reaction Pond I was calculated to be 3,830 lb. The total mass in the soil and water was calculated to be 2,530 lb and 1,300 lb, respectively.

Table D-4. Summary of Data Used to Make Total Mass Calculations at all Three Source Locations

	Reaction Pond I	Reaction Pond III	Well 21
θ_E	0.15	0.15	0.15
θ_A	0.25	0.25	0.25
C_s (ppb)	600,000	700	1,600
C_w (ppb)	3,000,000	3,500	8,000
Vol_s (ft^3)	46,250	35,650	35,650
γ_s (lb/ft^3)	121.5	121.5	121.5
γ_w (lb/ft^3)	62.4	62.5	121.5
Kd	0.2	0.2	0.2

Reaction Pond III

Based on the data in Table D-4, the total mass of TCE in the unsaturated zone at Reaction Pond III was calculated to be 3.5 lb. The total mass in the soil and water were calculated to be 2.3 lb and 1.2 lb, respectively.

Around Well 21

Based on the data in Table D-4, the total mass of TCE in the unsaturated zone around Well 21 was calculated to be 7.9 lb. The total mass in the soil and water were calculated to be 5.2 lb and 2.7 lb, respectively.

The estimated total mass of TCE present in the unsaturated zone (based on October 1982 soil analyses) at the three suspected source areas is summarized in Table D-5.

Table D-5. Summary of Estimated Total Mass of TCE Present at the Three Suspected Source Areas

	Mass of TCE (lb)		
	In Soil	In Water	Total
Reaction Pond I	2,530	1,300	3,830
Reaction Pond III	2.3	1.2	3.5
Around Well 21	5.2	2.7	7.9

LEACH DURATION AND AMOUNT FROM SOURCE LOCATIONS

The preceeding calculations show that Reaction Pond I is the only source location which contains a significant quantity of TCE in the unsaturated zone. Therefore, calculations to determine the time required for TCE to leach out of the unsaturated zone (duration), and the amount that would leach out each year were only made for Reaction Pond I. This information was used in the modeling to determine the length of time into the future to keep Reaction Pond I active, and the quantity of TCE to leach from the unsaturated to the saturated zone at each time step.

Reaction Pond I

The leach duration and amount calculations were based on the concentration of TCE in the water of the unsaturated zone and the rate of water movement through the unsaturated zone from annual recharge. Equation D-1 can be used to calculate the TCE concentration in the water (C_w) based on the total mass of TCE remaining in the system at any given point in time. For convenience, the equation can be rewritten as follows:

$$C_w = \frac{Mass_{TCE}}{Vol_s \{Kd\ (1 - \theta_A)\ \gamma_s + \theta_E\ \gamma_w\}} \qquad \text{(D-2)}$$

The volume of water (Vol_w) moving through the unsaturated zone from the average annual recharge was calculated as follows:

$$Vol_w = Rhg \times A = 6{,}167\ ft^3/yr$$

where

Rhg = average annual recharge (0.67 ft/yr - see Appendix A)
A = area of Reaction Pond I (9,250 ft^2)

This number was converted to a mass of water ($Mass_w$) passing through the unsaturated system so the units are consistent.

$$Mass_w = Vol_w \times \gamma_w = 384{,}800\ lb/yr$$