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# GROUNDWATER FLOW AND CONTAMINANT FATE AND TRANSPORT MODEL

# GRANVILLE SOLVENTS SITE GRANVILLE, OHIO

**Submitted to**

**The United States Environmental Protection Agency**
**Emergency Response Branch, Region V**
**Chicago, Illinois 60673**

**Developed for the**

**Granville Solvents PRP Group**
**One Columbus, 10 West Broad Street**
**Columbus, Ohio 43215-3435**

**December 20, 1996**


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# 1.0 INTRODUCTION

This report documents a groundwater flow and contaminant fate and transport model developed to evaluate options for remediation of impacted soils and groundwater at the Granville Solvents Site (GSS) in Granville, Ohio. The evaluation was conducted by Metcalf & Eddy, Inc. (M&E) on behalf of the Granville Solvents Site PRP Group, using the protocol described in a letter submitted to the U.S. EPA on September 11, 1996 (letter included in Appendix A), and confirmed by representatives of the U.S. EPA in a meeting on September 25, 1996. The Engineering Evaluation/Cost Analysis (EE/CA) being prepared will examine the alternatives and select one.

Groundwater and soil contamination have been identified and assessed at the GSS. The contamination resulted from activities at a former solvent recycling business located at this site. Impacted surficial soils at the site are believed to provide an ongoing source of contaminants to the groundwater.

Impact to the groundwater (and soil) is currently being remediated by the Granville Solvents Site PRP Group with a pump and treat remediation system, which has been in operation nearly two years. The system has contained the groundwater contaminant plume, preventing further migration toward Granville's wellfield and reducing the size and mass of the contaminant plume.

As long as the system remains active, contaminants from the GSS will not impact the wellfield. A groundwater modeling effort was not required to demonstrate this fact. Monthly potentiometric surface maps and routine groundwater monitoring have provided ample evidence of plume reduction and containment. With continued operation of the pump and treat system, the GSS will pose no further threat to human health and the environment.

Although the pump and treat remediation system at the GSS is sufficient to prevent off-site impact, it may not be the most cost effective long-term solution. The pump and treat system, acting alone, may require a very long period of time to remediate both the soils and groundwater. Alternatives exist for soil remediation which could significantly reduce the number

of years that the pump and treat system will need to operate, but these alternatives have associated costs. Therefore, optimization of the remediation effort is required to produce a more cost effective solution that will maintain the current high level of protection.

Optimization cannot be accomplished, however, without some means of establishing the interactions between soils and groundwater, and estimating clean-up times under a variety of remediation alternatives. A groundwater flow model and contaminant fate and transport model were selected as tools for estimating clean-up times for a variety of remediation alternatives. The objective of the modeling effort was to establish comparative times required to complete remediation. Comparative times for each alternative will subsequently be used to estimate comparative costs. This latter information will be presented in the EE/CA.

The modeling results obtained from this project will not be used to establish end times for the remediation efforts and will not be taken as substitutes for field evidence. Rather, the results are to be used to compare remedial alternatives on a common basis and make recommendations regarding the most favorable approach in terms of cost effectiveness and protection of human health and the environment. Ultimately, it will be the field evidence obtained from potentiometric maps and groundwater sampling data that will be used to establish the effectiveness of the remedial effort, verify the continued protection of the wellfield, and determine the time of completion of remediation.

## 2.0 CONCEPTUAL MODEL

The aquifer system at the GSS, which also supplies groundwater to the Village of Granville wells, is a buried valley aquifer. The permeable soils of the buried valley range from fine sands to sand and gravel occurring to depths of more than 250 feet. Groundwater production capabilities of the buried valley system are substantial. The bedrock valley walls and floor are composed of shale, which contributes minimally to water production in the valley (M&E, 1994).

The permeable aquifer deposits are overlain by a layer of silty clay soils of relatively low permeability. These soils are of fluvial origin and their thickness varies across the region. In the area of the GSS they are approximately 20 feet thick. These soils are saturated from near ground surface to the soil/aquifer interface.

In most of the buried valley aquifer, the groundwater in the aquifer is under confining pressure created by the overlying clayey soils. Water levels in most wells drilled in the aquifer rise to levels of 10 to 20 feet below the ground surface.

Through most of the region, saturated aquifer soils are in contact with saturated clay soils. Given the higher potentiometric head in the clay soils, it can be assumed that the aquifer receives some recharge from the overlying soils. The clay soils are saturated to near the ground surface. Due to the low permeability of the clay soil, much of the rainfall through the modeled area runs off the ground surface and leaves the area through Raccoon Creek. Water infiltrating the soil surface either proceeds at a slow rate to the aquifer or is removed by evapotranspiration.

Raccoon Creek appears to be largely isolated from the aquifer. It is believed that, under normal flow conditions, the stream is losing through the modeled region. Under flooding conditions, there is evidence that the creek recharges the aquifer.

# 3.0 GROUNDWATER FLOW AND CONTAMINANT FATE AND TRANSPORT MODEL

## 3.1 MODELING SOFTWARE

The primary objective of the modeling project was to provide a means for comparing remedial alternatives. The critical factor in the comparisons involved the interaction between the low permeability surface soils and the aquifer. The soils at the GSS site contain significant concentrations of chlorinated and other compounds that are slowly contributing dissolved phase solvents to the aquifer. Given the need to model the interaction between the soils and the aquifer, a numerical model was chosen. This type of interaction can be effectively handled with a numerical model, but is beyond the capabilities of analytical models.

MODFLOW was chosen as the numerical flow model for this project. MODFLOW is the standard numerical groundwater flow model commonly in use today. It has been thoroughly tested and widely accepted by industry, consultants, and the regulatory community. Visual MODFLOW, a graphical interface for MODFLOW, MODPATH, and MT3D, was used for importing data to the model and graphically portraying the results.

MODPATH was also used for establishing flowpaths within the model and establishing times of advective travel along the flowlines. A program known as MT3D[96] was used for contaminant fate and transport modeling. This newly updated fate and transport code incorporates the features of the older versions of MT3D with new options and algorithms to facilitate more complex simulations.

The procedures used to implement the models and the specific parameters chosen for the initial set-up of the model are described in this section. Final model inputs, following calibration are presented in Section 4.0.

## 3.2 MODFLOW MODEL SET-UP

Each aspect of the model set-up is described here with specific parameter choices described and supported. In general, where model input was required which was not known from tests at the GSS, assumptions were used which would increase the probability of the model predicting impact to the Granville wellfield. Some extrapolation of parameters known from investigations at the GSS was necessary to expand the model through the region. Data from other sources (the regional glacial map, the regional bedrock map, water well logs, oil and gas boring logs, etc.) were used where possible.

### 3.2.1. Modeled Area and Grid

The model grid encompasses an area of approximately 2 square miles surrounding the GSS. The area away from the pumping centers was gridded in 250 feet cells. Within the pumping centers the grid was refined to cells with width and length of 50 feet. Figure 1 depicts the model grid and shows the locations of GSS extraction wells and the Granville production wells. Figure 2 provides an enlargement of the primary area of interest, extending from the GSS through the Granville wellfield.

### 3.2.2 Model Layers

The model was divided vertically into 10 layers. The upper five layers depict the clay rich soil overlying the aquifer and were given identical input parameters due to the relative homogeneity of the soils (determined based on the results of the soil sampling program at the site). The reason for dividing the clay soil into separate layers was to provide a higher level of resolution for soil contaminant concentrations within the soil column. The lower five layers of the model represent the soil and gravel of the buried valley aquifer.

### 3.2.3 Boundary Conditions

Aquifer Boundary Conditions

Two types of boundary conditions, no-flow and constant head, were used in modeling the aquifer system. The locations of no-flow and constant head boundaries are included on Figure 1. No-flow boundaries were used at the bedrock walls of the buried valley system. The bedrock is composed of the Raccoon Shale, which is of very low permeability, compared to the highly permeable sand and gravel of the buried valley aquifer. For this reason, it was appropriate to designate the bedrock walls as no-flow boundaries in the model. This designation was made for all model layers.

The location of the bedrock walls was based on area topography, a bedrock surface map, oil and gas exploration borings, and the experience of M&E staff geologists with this buried valley system. The Glacial Map of Licking County (Ohio Division of Geological Survey[1]) is included for reference as Plate 1. The glacial map includes bedrock surface elevations for the buried valley system. It also depicts the character of the glacial soils present in the valley.

One deviation from the outline of the bedrock valley was made to exclude a small buried tributary valley which enters the main valley from the south near the middle of the modeled region. The bedrock surface map indicates that this tributary valley is about the same depth as the main valley. However, the glacial deposits in the tributary valley are known to be of relatively low permeability based on a review of borings and water well records. The sediments in the tributary valley supply a few domestic wells with relatively low production rates, but these wells appear to be completed in sand and gravel lenses within a till or clay matrix. Therefore, the tributary valley was modeled as a barrier boundary similar to the bedrock walls of the main valley.

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[1] Reference is to Ohio Division of Geological Survey, Report of Investigation No. 59, by Jane L. Forsyth, titled *Glacial Map of Licking County, Ohio*. Undated.

The floor of the main bedrock valley was also modeled as a no-flow boundary. Depth to the bedrock floor in the modeled region was established based on the bedrock map provided on Plate 1, available oil and gas exploration boring logs, and borings completed as a part of the investigations at the GSS and the Granville wellfield. The bedrock surface was entered into the model as the bottom of model layer 10.

Constant head flow boundaries were arbitrarily established transverse to the main buried valley above and below the modeled area. This allowed flow into and out of the area through the aquifer. No information was available regarding the downvalley regional gradient in the buried valley beyond the pumping influence. The direction of flow of Raccoon Creek is from west to east, and it can be presumed that the regional gradient would also be to the east. However, in keeping with the decision to provide assumptions that increase the probability of the model predicting impact to the wellfield, constant head flow boundaries at the same elevation were chosen for the east and west boundaries of the valley. Under background (non-pumping) conditions, these levels would have resulted in no gradient either up or down the valley. Any background gradient in this system would probably be from west to east and tend to lessen the influence of the Granville wells on the groundwater flow at the GSS. The constant head flow boundaries are far enough from the pumping centers to have only minimal influence on model results.

As shown on the glacial map (Plate 1), Raccoon Creek flows through the central portion of the valley in most of the modeled area. The creek turns northward near the GSS and flows eastward in a course that lies just south of the site. This represents the closest approach of the creek to the site and the northern boundary of the buried valley system within the modeled area.

Raccoon Creek was not included in the model. The choice not to include the creek was based on information obtained from pumping tests which indicated that the creek does not interact significantly with the aquifer under pumping conditions (M&E, 1995). If interaction were present between the creek and the aquifer, the creek would be a losing stream through the modeled area based on relative water levels. Water added to the aquifer from the stream would tend to diminish the effects of the Granville wells on the aquifer beneath the GSS. Thus,

excluding the creek from consideration in the model increased the probability of the model predicting impact to the wellfield from the GSS.

Upper Soils Boundary Conditions

No-flow boundaries were used on all horizontal edges of layers comprising the clay-rich upper soils. Given the low permeability of these soils, the choice of boundary conditions in a regional model is insignificant.

Constant head cells were also used vertically as the top layer of the clay soils to provide a stable means of introducing recharge to the system. The use of a constant head boundary to represent recharge is discussed in detail below.

### 3.2.4. Village of Granville Wellfield

Wells for the Village of Granville were placed in the model at their appropriate locations within the modeled area and screened at the appropriate depths within the aquifer. The pumping rates for the wells for calibration runs were based on the rates reported for the 98 hour GSS pumping test. For model prediction runs, the overall pumping rate of the wellfield was distributed between the three supply wells according to their respective productive capacities (i.e., well PW-3 accounted for less production than wells PW-2 and PW-4). In practice, the wells are alternated and each well is pumped at a rate significantly exceeding Village demands. Pumping is therefore intermittent throughout the course of a given day. For the model, however, each well was assumed to pump at a constant rate, and the total pumping rate for the combined wells was matched to their average pumping rate. In keeping with the desire to remain conservative in the model set-up, the total pumping rate was assumed to be twice the current pumping rate for model predictions. The duration of the model runs was typically 30 years into the future. It was assumed that production of the wellfield would remain within a factor of two of the current average pumping rate throughout this 30 year period.

### 3.2.5 Recharge

Recharge could not be stably implemented through the use of the MODFLOW recharge package because of the low permeability of the upper clay soil. However, the upper clay soil is known to be saturated from a few feet below the surface to the interface with the aquifer, based on soil moisture values obtained from Shelby tube samples. Given this condition, a consistent gradient will be present through the clay soils to the aquifer interface. This condition was approximated using constant head boundaries at the surface which represent the "water table" within the clay soil. Recharge is largely independent of rainfall conditions. Rainfall in excess of the very low infiltration rate of the soils simply runs off the surface. The clay soil slowly transmits water between a constant head source at the level of saturation and a variable head sink at the interface with the aquifer.

Groundwater flow through the clay soils to the aquifer carries contaminants from the soils to the aquifer. Therefore, the proper representation of flow in the clay soils is essential for making valid predictions regarding how the soils interact with groundwater and bring new contaminants to the groundwater system. The subject of flow through the clay soils is addressed thoroughly in the sensitivity analysis of this model and in model runs comparing the remedial alternatives.

### 3.2.5 Hydraulic Conductivity

The transmissivity of the aquifer was established from pumping tests at the GSS using observation wells within the GSS and portions of the Granville wellfield. The transmissivity values were input into the model in terms of hydraulic conductivity values for each model layer within the aquifer. Based on boring logs at the GSS and the Granville wellfield, the lower portion is the most permeable part of the aquifer. Therefore, for the initial model set-up, the hydraulic conductivity of the lower two model layers (layers 9 and 10) was set higher than the conductivity of the upper three aquifer layers (layers 6,7 and 8). The conductivities were chosen such that the combined transmissivity of the model layers matched the results of the pumping tests.

The hydraulic conductivity of the overlying clay soil layers (layers 1 - 5) was based on laboratory permeability tests of Shelby tube samples collected in the most recent soil sampling program. Twelve laboratory permeability tests were conducted. The hydraulic conductivity determined by these tests ranged from $1 \times 10^{-8}$ to $9 \times 10^{-8}$ cm/sec. However, it is not uncommon for laboratory permeability tests to underestimate the conductivity of a clay soil, and it is likely that the true permeability of these soils is somewhat higher than that shown by the tests. Thus, for the initial model the conductivity of the clay soil layers was set at $1 \times 10^{-7}$ cm/sec.

As discussed above, the vertical flow of water through the clay soil layers is a critical factor in determining the results of the model. A degree of uncertainty in the hydraulic conductivity of these layers is inherent due to the difficulty involved in obtaining reliable conductivity values for low permeability soils. The conductivity value presented above was an appropriate value to enter as an initial estimate and represents the best data available. However, a wide range of conductivity values for the clay soils was evaluated as a part of the sensitivity analysis and a similarly wide range of values was taken to the final stage of the model where the alternatives were compared. As a result, the initial estimate of conductivity for the clay soils is of little consequence. Ultimately, the clay soils were treated in such a way as to maintain a high level of uncertainty in their rates of conductance and still provide meaningful comparisons of the alternatives.

### 3.2.6 Storativity, Specific Yield, and Porosity

For the layers representing the aquifer (layers 6 - 10), the initial storativity and specific yield values were estimated from the GSS pumping test analyses. A 30 percent porosity was assumed, consistent with textbook values typically given for this type of aquifer (Fetter, 1988; Freeze, 1979).

For the clay layers, estimated values of porosity, storativity, and specific yield were used. The porosity of clay rich soils was estimated at 35 percent (Fetter, 1988; Freeze, 1979). The storativity was assumed to be 0.001 and the specific yield as 0.01 percent. No reliable field

method exists for determining storativity in low permeability soils. The specific yield used may appear relatively small in comparison to typical specific yield values for permeable soils. However, little water drains from low permeability clay-rich soils after they reach field capacity (the water holding capacity following gravity drainage). Water enters these surficial soils in response to rainfall, and is removed largely by evapotranspiration during the growing season. The transition between full saturation and field capacity represents the loss of only a very small amount of water in these soils, which is reflected by the low specific yield used in the model.

## 3.3 MT3D MODEL SET-UP

### 3.3.1 Contaminant Analyzed

The soil and groundwater contaminant chosen for analysis in the model was trichloroethylene (TCE). The choice of this compound was consistent with providing the "worst case" comparison. Several contaminant compounds have been identified in field investigations at the GSS. These compounds include: trichloroethylene, tetrachloroethylene, 1,1,1-trichloroethane, trans-1,2-dichloroethylene, cis-1,2-dichloroethylene, 1,1-dichloroethylene, 1,1-dichloroethane, methylene chloride, chloroform, vinyl chloride, carbon disulfide, acetone, 2-butanone, r-methyl-2-pentanone, ethylbenzene, toluene, and xylene. Distribution of these contaminants in the aquifer and the overlying soils has been investigated and reported (M&E, 1994; M&E, 1996).

TCE is the most highly concentrated and wide-spread compound in both the soil and groundwater at the GSS (M&E, 1994; M&E, 1996) . It has a low permissible Maximum Contaminant Level (MCL) of 5 $\mu$g/L. Tetrachloroethylene (PCE) also has a MCL of 5 $\mu$g/L; however, the PCE is lower in concentration than TCE in both soils and groundwater, and PCE is retarded to a greater extent in the soils than is TCE. Based on this information, TCE represents the "worst case" compound for potential impact to the Village of Granville wellfield.

### 3.3.2 Initial Concentrations of TCE

The initial concentrations of TCE assigned to the aquifer layers of the model were based on the concentrations analyzed at the GSS in the Hydropunch® study (M&E, 1994). This study was completed in 1994 and probably does not represent current concentrations after operation of the pump and treat remediation system for nearly two years. The GSS monitoring wells have shown a decline in TCE concentrations since pumping was started. However, the most complete analysis of the distribution of TCE in the aquifer was from the Hydropunch® study, and to increase the probability of the model predicting wellfield impact, these values were used in the model.

The TCE concentrations assigned to the clay soil layers of the model were based on a soil investigation in the spring of 1996. Results of this investigation are reported elsewhere (M&E, 1996). The sample depths in each boring were extrapolated to the level of the model layers. Where soil samples had not been taken directly at the elevation of a model layer, the samples taken above and below the given elevation were examined and the higher concentration of the two was used. The sample locations for each layer were plotted on a map and contoured to provide a concentration distribution for each layer, which was digitized and imported into the model. The closely spaced sampling points were extrapolated to the model grid with the overall concentration of TCE being conserved.

The boring program at the GSS involved a relatively close spacing of boring locations, and specialized techniques were used to detect DNAPLs. DNAPL was not detected. Moreover, the concentrations of solvents in the soils were low enough that DNAPLs are not expected to be present. Therefore, potential effects of DNAPL were not incorporated into the model.

However, it is rarely possible to conclude with certainty that DNAPLs are not present in a soil subject to free phase releases. While the potential presence of DNAPL was not directly analyzed by the model, it was considered qualitatively with respect to the scenarios presented in Section 6.

### 3.3.3 TCE Adsorption by Soils

The adsorption and retardation of TCE by organic carbon in the soils was addressed in the model through the use of linear isotherms. The sorption constant for the clay-rich soils was input as 0.0428 $ft^3/kg$, and the bulk density of the soils was input as 58.2 $kg/ft^3$. The value for bulk density was based on an average of 12 samples collected in the soil sampling program. The sorption constant is a calculated constant, based on the organic content of the soil and the distribution coefficient of the contaminant. The average organic carbon content of the clay soils was 0.8 percent based on 21 samples from the soil boring program. The octanol/water partition coefficient for TCE is 152 mL/g (Fetter, 1988). The sorption constant was then calculated from these data and entered into the model.

The sorption constant used for the aquifer soils was 0.00268 $ft^3/kg$. This sorption constant was calculated using an assumed bulk density of 56.5 $kg/ft^3$ and an assumed carbon content of 0.05 percent. The difference between the sorption constant for the aquifer soils and the clay-rich soils is due to the lower organic carbon content of the aquifer soils. The assumed organic carbon content of the aquifer (0.05 percent) is consistent for this type of aquifer soil. The effect of varying this assumed value is addressed in the sensitivity analysis. Bulk density varies within a relatively narrow range and its variability has little effect on model outcome.

### 3.3.4 Degradation

TCE does not degrade abiotically to any great extent. Some abiotic degradation has been cited in the literature, but these values have been called into question by more recent studies (Jeffers, 1989). It is now generally accepted that the abiotic degradation of TCE is slow enough to be neglected.

Biological degradation of TCE has been frequently reported (Tabak, 1989, Little, 1988, Wackett, 1989, Harker, 1990, Vannelli, 1990, etc.). Such degradation occurs in conjunction with biological degradation of other hydrocarbons or under anaerobic conditions. Evidence of biological degradation is present at the GSS. Cis-1,2-dichloroethane (cis-1,2-DCA) is present

in the aquifer near EW-1. Small concentrations of this compound were present during the initial studies and the concentrations have increased over time. Cis-1,2-DCA is only produced biologically from degradation of more highly chlorinated compounds.

Although clear evidence of biological degradation is available, there is no way to reasonably quantify the degradation rate. A small degradation constant could have been justified for the model given the site evidence. However, the assumption of no degradation was entered into the model in order to increase the probability of the model predicting impact to the Granville wellfield. The sensitivity of the model to degradation is evaluated in Section 5.

### 3.3.5 Dispersion and Diffusion

Reliable values of dispersion and diffusion are rarely available for input to a fate and transport model. Occasionally the values can be backed out of fate and transport calibration procedures when a great deal is known about the nature, timing, and duration of a chemical release. For this site, this level of detail about releases was not available. An assumed value of 10 feet was used for longitudinal dispersivity. The transverse dispersivity was assumed to be ten percent of the longitudinal dispersivity and the vertical dispersivity was assumed to be 1 percent of the longitudinal dispersivity for the aquifer and ten percent for the upper clay soils. These values all represent assumptions which are reasonable for the conditions at the GSS and are in line with common practice. The uncertainty introduced by using these assumed values is addressed in the sensitivity analysis presented in Section 5.

Site-specific values for molecular diffusion were not available. This is nearly always true in site investigations, and this parameter is not generally considered to be significant. A text book value of $9.3 \times 10^{-5}$ $ft^2/day$ ($1 \times 10^{-7}$ $cm^2/sec$) was used for all model layers (Domenico, 1990). The effects of varying this value are addressed in the sensitivity analysis in Section 5.

# 4.0 MODEL CALIBRATION

The flow model was calibrated to pumping test data from the GSS. As discussed above, the contaminant fate and transport model could not be calibrated due to the lack of specific data regarding the nature, timing and duration of the contaminant releases. The effect on the model results of not being able to calibrate the fate and transport model is addressed in Section 6.

The flow model was calibrated based on the 98-hour pumping test of extraction well EW-1 between December 30, 1994 and January 2, 1995. The duration of the test, the location of EW-1 between the GSS and the City of Granville wellfield, and the large number of observation wells used in the test, made this an ideal test for model calibration. A brief description of the 98-hour pumping test and a description of the methods and results of the model calibration are provided below.

## 4.1 98-HOUR PUMPING TEST

Details and results of the 98-hour pumping test of well EW-1 are provided in *Removal Action Aquifer Pumping Test Report* (M&E, 1995). Drawdown data for 15 wells were available from this test for comparison to model runs which mimicked the same pumping conditions. During the test, Granville pumping well PW-3 was pumped at an average rate of 260 gpm. The well was actually pumped at a higher rate for portions of each day and then rested between cycles, but it was noted at the time that the pumping cycles (of PW-3) did not affect the observation wells at the GSS. Therefore, for the purpose of model calibration, well PW-3 was assumed to pump continuously at its average rate during the 98-hour test.

Extraction well EW-1 was pumped at a constant rate of 200 gpm for the duration of the 98-hour test. Recovery data were not available from this test because pumping continued after 98 hours as a long term test of EW-1 and EW-2 pumping together. For simplicity in the process of matching the data, only the 98-hour interval was used for model calibration.

Plate 2 shows the potentiometric surface at the GSS at the end of the 98-hour pumping test. This configuration was use for qualitative matching to the model. Data from the 15 observation wells used for the calibration are listed in Appendix D of the pumping test report (M&E, 1995). Plots of the pumping test data are provided in Figures 3 through 7, where they are compared to the model predictions.

## 4.2 CALIBRATION METHODS

To calibrate the model, model runs were completed and the head data generated by MODFLOW were compared to the head data from each observation well in time series plots. The accuracy of the matches were evaluated qualitatively. The model parameters of hydraulic conductivity (horizontal and vertical), storativity, and specific yield were varied systematically until a good fit between the pumping test data and the model predictions was obtained.

The match between pumping test data and the model predictions was considered more accurate for certain wells than for others. In general, the wells closest to EW-1 were discarded from the matching procedure, due primarily to the coarse nature of the model grid and to the difficulty of obtaining accurate estimates of data at specific locations close to the pumping center. With greater distances from the well, the problem of differentiation becomes less important.

Wells located close to the pumping center also have problems related to their vertical location within the model layers. Most observation wells had short screens (generally 10 feet long), and some were located near the interface between layers or across the interface. The model averages results over the full layer (or layers) which contains the well screen. For wells close to the pumping center, this can result in inaccuracy in model predictions compared to the pumping test data. This would not mean that the model is providing incorrect interpretation of the aquifer, but shows that the model is not able to provide resolution on the same scale as the data from the test for wells located close to the pumping center.

Wells GSS-P1, GSS-P2, GSS-MW2, and MW-7D were considered too close to the pumping center to provide adequate resolution within the model and were not considered in the model

calibration procedure. Well MW-3 is completed in a perched zone above the aquifer and also was excluded from model calibration.

The following wells provided the data from the 98-hour pumping test for model calibration: PW-1, MW-8D, STANS, MW-2D, MW-6D, MW-P1, GSS-EW2, MW-1, and MW-5. These wells span a distance of approximately 1,150 feet across the GSS and into the Granville Wellfield (well PW-1 is a former Granville production well). The observation wells also surround well EW-1 in four directions.

## 4.3 CALIBRATED MODEL MATCH TO PUMPING TEST DATA

Based on the calibration model runs, parameter values were adjusted, by layer, to obtain accurate fits to the pumping test data. Alteration of parameter values in individual cells within model layers was not attempted. Such alterations would likely have provided a closer match to the data, but it was decided that empirical site data did not provide sufficient justification for this level of alteration.

Data from the pumping test were plotted as time series plots for each observation well as shown in Figures 3 to 7. Simulated data from the model runs were compared to the field data in the time series plots. With a few exceptions, these plots show good matches between calibrated model predictions and the field data. The largest deviation of the model prediction from the field data was about a tenth of a foot. Even wells that show deviation from the field data show the same trend as the field data. The only well with significant deviation that does not show a similar trend is well MW-2D. This well shows a trend of continuing decline at the end of the test without a tendency for the data to flatten out. This trend is not consistent with other observation wells at the site and may have been the result of a malfunctioning transducer used for data collection.

Table 1 provides the final values used in the calibrated model for each parameter in each model layer. Note that most of the input values were not subject to calibration; only hydraulic conductivity, storativity, and specific yield were included in the model calibration procedure.

Data were not available to conduct a calibration on the remaining parameters. Parameters, including those not subject to calibration, are addressed in detail in the sensitivity analysis in Section 5.

# 5.0 SENSITIVITY ANALYSIS

The primary purpose of a sensitivity analysis is to identify those parameters which can have significant effects on the conclusions of the model but which are not adequately defined by model calibration (ASTM, 1994). Four types of model parameter sensitivity are commonly considered (ASTM, 1994).

A type I sensitivity is assigned to a model parameter if its variation causes little or no change in either the quality of the calibration or the model conclusions. This type of parameter is of no concern because it has no bearing on conclusions made based on the model results.

A model parameter is given a type II sensitivity if its variation causes significant changes in the calibration of the model but does not effect the model conclusions. This type of parameter is of no concern because it does not affect the model conclusions and is generally handled adequately in the calibration procedure.

A model parameter has a type III sensitivity if its variation causes significant changes in the model calibration and corresponding, correlatable changes in the model results. This type of parameter is also of no concern because it should be handled well by the model calibration. The calibrated model should provide correct simulations with respect to this type of parameter.

A model parameter has a type IV sensitivity if its variation causes insignificant changes to the model calibration but causes significant changes in the model conclusions. This type of sensitivity can invalidate the results of a model because the calibration procedure does not adequately address this parameter and variation of the parameter can change the model conclusions. This type of parameter must be thoroughly addressed for the simulations to be considered valid.

This section discusses the methods, results, and conclusions of the sensitivity analysis of this model.

## 5.1 PARAMETERS VARIED IN SENSITIVITY ANALYSIS

All of the primary parameters used in the flow and fate and transport models were varied as a part of the sensitivity analysis. The effects of this variation with respect to model calibration and simulations were recorded. The parameters were then grouped according to the type of sensitivity they exhibited. Those identified as having type IV sensitivity were singled out for further analysis and discussion.

Parameters varied in the sensitivity analysis included: horizontal hydraulic conductivity of the aquifer, vertical hydraulic conductivity of the upper clay soils and of the aquifer, storativity, specific yield, porosity, dispersion coefficient, sorption constant, degradation, and molecular diffusion.

## 5.2 METHODS USED TO COMPLETE THE SENSITIVITY ANALYSIS

To conduct the sensitivity analysis, it was necessary to establish a base scenario that would result in plume generation. Then the plume generated by each model run in which a parameter value had been changed could be compared to the base scenario to determine if a significant change in the simulations had occurred.

The basic scenario included the pumping the Granville wellfield at an average rate of 1.5 million gallons per day (mgd) throughout the length of the model run, and pumping EW-2 at a rate of 320 gpm for five years. Each sensitivity simulation was run through 30 years (25 years after EW-2 was shut down). This scenario does not correspond to any of the alternatives evaluated in the next section. Pumping for only five years without any soil remediation was expected to result in plume generation under nearly all values of model input parameters. This was a desirable condition for the sensitivity analysis. It allowed easy comparison between the outcome for the base scenario and the outcome when a given parameter was varied.

The aquifer concentrations of TCE were recorded for each year between five and ten years after the start of the scenario (between zero and five years after EW-2 was shut down), and at 10, 15,

20, 25, and 30 years after each model run began. The initial head values for the start of the simulation were steady state values obtained from a previous steady state model run. Figure 8 shows the steady state potentiometric surface for layer 6 of the model.

The model output was evaluated for the location of the 5 $\mu$g/L plume (plume above MCL for TCE). The maximum extent of the plume in each layer of the aquifer was determined and recorded for each simulation. In nearly all instances, maximum migration occurred in layer 6 of the model, the top layer of the aquifer, but all layers were checked for migration distances. The time interval in which the maximum migration occurred was also recorded. If model simulation with a varied parameter resulted in a change greater than 50 percent (from the base model) in the distance of maximum plume migration, it was concluded that the given variation in the parameter had a significant effect on the model. The distance of migration and shape of the 5 $\mu$g/l plume for the base model, at maximum migration, are presented in Figure 9.

For other parameters which also had an effect on model calibration, the model was run in the same manner as described in Section 4 with the new parameter value being evaluated for sensitivity. The resulting matches to the pumping test data were observed. If the change in the parameter caused the match between the pumping test data and the model prediction to become significantly less accurate for more than 50 percent of the observation wells, the parameter variation was considered to have significantly affected the model calibration.

## 5.3 RESULTS OF THE SENSITIVITY ANALYSIS

Following completion of the sensitivity runs, the results of each run, with respect to model calibration, were tabulated and a sensitivity type was assigned to each run. Table 2 provides the results of the sensitivity analyses. The parameters analyzed are grouped with respect to their type of sensitivity. Ten model runs for six parameters showed type I sensitivity. The parameters showing type I sensitivity were the following:

- biological degradation (at 0.0002 L/day for sorbed phase and 0.00002 L/day for nonsorbed)

- longitudinal dispersivity at one fifth the value used in the calibrated model,
- molecular diffusion at 0.1 times, 10 times and 100 times the value used in the calibrated model,
- porosity at 0.83 times (25 percent) and 1.17 times (35 percent) the value used in the calibrated model,
- sorption constant at five times and one fifth the value used in the calibrated model,
- specific yield at 0.5 times and 1.5 times the value used in the calibrated model.
- porosity at 1.17 times and 0.83 times the value used in the calibrated model.

Storativity showed type II sensitivity at one tenth and ten times the value used in the calibrated model. Horizontal conductivity in the aquifer showed type III sensitivity when varied between three quarters and two times the value used in the calibrated model. Vertical conductivity in the aquifer also showed type III sensitivity when varied by an order of magnitude in either direction from the value used in the calibrated model.

The above parameters, with type I, type II, and type III sensitivity, were of no concern with respect to the model conclusions. The variation of these parameters either had no influence on model conclusions, or had a significant influence on both the model conclusions and the calibration of the model.

The following parameters show type IV sensitivity and are of considerable importance to the results of the model:

- biological degradation when given values of 0.002 L/day for sorbed and 0.0002 L/day for nonsorbed,
- longitudinal dispersivity when set at five times the value used in the calibrated model, and
- vertical hydraulic conductivity of the upper clay soils when set between 0.01 and 2 times the value used in the calibrated model.

The results of the sensitivity analysis for biological degradation suggest that leaving this factor out of the model may result in an over-prediction of impact at the Granville wellfield from the GSS.

Using higher values of longitudinal dispersivity would also result in an indication of less impact to the wellfield from the GSS. Lower values of longitudinal dispersivity did not result in a significant increase in plume migration.

The most important sensitivity in this model is its sensitivity to vertical hydraulic conductivity of the upper clay soils. This parameter was varied over a wide range due to the uncertainty in methods available to estimate it and the uncertainties associated with the manner in which flow through these layers was modeled. Overall, the range of variation in hydraulic conductivity used in the sensitivity analysis covered thoroughly the possible outcomes for the leaching of contaminants from the upper clay soils.

A wide range of possibilities for contaminant transport through the clay were explored in the sensitivity analysis. When the vertical conductivity of the clay soils was set at $1 \times 10^{-7}$ cm/sec (0.00028 ft/day), close to the value obtained from the laboratory vertical permeability tests, the model showed a maximum plume migration of only 102 feet after five years of pumping. The flux of contaminants was barely sufficient, at this value, to create a plume. When the hydraulic conductivity was increased by a factor of 10 (to $1 \times 10^{-6}$ cm/sec), a small plume extending to a maximum distance of 235 feet was formed. Further increasing the conductivity, to the value used in the base scenario ($1 \times 10^{-5}$ cm/sec), resulted in a maximum plume generation of 541 feet. However, a further increase in the vertical conductivity to $2 \times 10^{-5}$ cm/sec then diminished the maximum plume extent to 374 feet. Thus, a very large range of possibilities for TCE flux was explored. The vertical conductivity value used in the base scenario was shown to be approximately the worst case value for plume generation and migration.

The reason for the diminishing affect for this parameter beyond a critical value may not be apparent from the data presented in Table 2, but is made clear by observing the concentration of TCE left in the soils under the various scenarios. With the vertical conductivity of the upper

clays soils set at a low value (similar to the value obtained from the laboratory permeability tests), the flux of TCE from the soils to the aquifer is barely sufficient to form a small plume after five years of pumping. However, 20 years after pumping stops, the model still indicates a relatively high concentration of TCE remaining in the soils.

With the vertical conductivity of the upper clay soils set at a reasonably high value, of $1 \times 10^{-5}$ cm/sec, the flux rate and remaining TCE in the soil after five years of pumping combined to produce the maximum plume. As the conductivity was increased further (to $2 \times 10^{-5}$ cm/sec or greater) the flux of TCE from the clay soils in the first five years pumping was high enough that the quantity of TCE remaining in the soil when pumping ceased was not sufficient to generate a plume as large as that of the calibrated model. For both of these latter cases, the concentration of TCE remaining in the clay soils after 20 years is relatively small.

Two key conclusions can be made as a result of the sensitivity analysis in which the vertical conductivity in the upper clay soils was varied. The first conclusion is that uncertainty in the vertical permeability of the upper clay soils places it in a type IV sensitivity category. Proper choice of values for this parameter is critical for obtaining realistic model results. The second conclusion is that a worst case value for vertical conductivity of the clay can be obtained for each alternative scenario. Thus, even though a high degree of uncertainty is present regarding TCE flux from the upper soils, alternative scenarios can be compared in terms of worst cases. This is the methodology that was adopted for the final stage of the modeling, as discussed in Section 6.

## 5.4 FACTORS NOT CONSIDERED IN THE SENSITIVITY ANALYSIS

Only those factors which can properly be included in groundwater flow and contaminant fate and transport models were considered in the sensitivity analysis. Other factors, though they may have a bearing on an overall remediation strategy, could not be evaluated by this model. The most important such factor is the chance that DNAPLs may be present in the soils. Site investigation has not indicated the presence of DNAPL.

However, if DNAPL were to be present, it could change conclusions based on the results of the model runs in ways not subject to sensitivity control. The presence of DNAPL would not affect each scenario equally. Changes in the model-based conclusions that would stem from the presence of DNAPLs are discussed with each alternative presented in Section 6.

# 6.0 EVALUATION OF ALTERNATIVES

Four alternative scenarios with different methods of treatment for the upper clay soils and the aquifer are presented in this section. The alternatives are compared using the calibrated flow model discussed above. In all simulations, the Granville wellfield was pumped at a constant rate of 1.5 mgd distributed among the three pumping wells (PW-2, PW-3, and PW-4). The type IV sensitivity to vertical hydraulic conductivity discussed in Section 5 was independently evaluated for all but the no-action alternative. The potential effect of DNAPLs in the soils is evaluated for each alternative.

## 6.1 ALTERNATIVE 1 - NO ACTION

This alternative is presented only for comparison. The alternative involves an end to pumping from extraction wells at the GSS and the movement of contaminated groundwater toward the Granville wellfield. The calibrated model, with the upper clay soil vertical conductivity set at 0.028 ft/day was used for the initial simulation. The initial concentrations of TCE used for the aquifer in the calibrated model were based on two-year-old sampling data for the aquifer. Given that the pump and treat system has removed some of the TCE mass in two years of operation, the plume generation indicated for this scenario is probably overestimated. Actually, this simulation more closely approximates conditions where no treatment system had been installed at the GSS.

The results of this simulation indicated the arrival of groundwater above 5 $\mu$g/L in TCE concentrations at Granville wellfield (well PW-2) within 6 years. The TCE impact (above 5 $\mu$g/L) spreads to well PW-3 and continues through the 30 year period of the simulation. Well PW-4 was not impacted in this simulation, because wells PW-2 and PW-3 intercepted the plume. Realistically, if wells PW-2 and PW-3 were to become impacted, those wells would be sequentially shut down and well PW-4 would become impacted.

## 6.2 ALTERNATIVE 2 - MAINTENANCE PUMPING

The calibrated model was used to evaluate the alternative in which extraction well EW-2 is pumped at 320 gpm for 5 years and then pumped at a maintenance level of 40 gpm for an additional 15 years. Flux from the clay soils to the pumping well was allowed over the entire model run. This alternative was evaluated at each of three vertical hydraulic conductivity values for the upper clay soils. The values were varied by two orders of magnitude from 1 x $10^{-5}$ cm/sec to 1 x $10^{-7}$ cm/sec. These conductivity values are assumed to cover reasonable level of uncertainty for this type IV parameter.

The simulation using a vertical hydraulic conductivity in the upper soils of 1 x $10^{-5}$ cm/sec resulted in no regeneration of the 5 $\mu$g/L plume after pumping ceased in 20 years. Only a small mass of TCE remained in the upper clay soils after 30 years. The maximum TCE concentration in the pore water of the clay soil was 60 $\mu$g/L after 20 years and declined to 18 $\mu$g/L after 30 years.

The simulation using a vertical hydraulic conductivity for the upper clay soils of 1 x $10^{-6}$ cm/sec resulted in slight plume regeneration after 20 years of pumping. The maximum horizontal extent of the 5 $\mu$g/L plume was 125 feet from the edge of the impacted clay soil and remained within the bounds of the GSS. The maximum depth of the 5 $\mu$g/L plume was 885 feet amsl or about 15 feet below the top of the aquifer. After 20 years, the maximum TCE concentration in the upper clay soil pore water was 200 $\mu$g/L. After 30 years the maximum concentration had declined to 160 $\mu$g/L.

The simulation using a vertical hydraulic conductivity in the upper clay soils of 1 x $10^{-7}$ cm/sec (approximately the value obtained from the laboratory vertical permeability tests) resulted in a slight plume regeneration after 30 years. The maximum extent of the 5 $\mu$g/L plume was approximately 90 feet. However, a relatively large concentration of TCE remained in the soils after 30 years (1,600 $\mu$g/kg). To ensure that the plume would not extend farther after 30 years, the simulation was continued to 60 years. The maximum plume extent after 32 years was 105 feet, and its maximum depth was to elevation 889 feet amsl, or about 11 feet below the top of

the aquifer. At 60 years in the simulation, the maximum TCE concentration was 1,000 $\mu$g/kg in the upper clay soils.

The range of values for vertical conductivity of the upper clay soils was sufficient to include all reasonable outcomes on which to base conclusions. Conductivities higher than 1 x $10^{-5}$ cm/sec would result in no plume regeneration at 20 years due to the small TCE mass remaining in the clay soils after 20 years of leaching. Conductivities lower than 1 x $10^{-7}$ cm/sec would result in little or no plume generation due to the very slow addition of TCE from the upper clay soils. The plume resulting from simulation with a vertical conductivity of 1 x $10^{-6}$ cm/sec for the upper clay soils was the largest for the three simulations and represents the worst case scenario for these alternatives. That scenario resulted in a small plume that remained confined to the GSS property.

The affects of potential DNAPLs on the outcome of this scenario could be significant. The affect on each of the three simulations would be to provide more TCE mass in the soil at the end of the 20 year period. In all simulations, this would result in the generation of a larger plume.

## 6.3 ALTERNATIVE 3 - SOIL REMEDIATION TO 1,000 $\mu$G/KG TCE

This alternative involved soil treatment or removal for soils with TCE concentrations greater than 1,000 $\mu$g/kg. When deep soils are treated or removed, the soils above them were assumed also to be treated, even if the shallower soils had TCE concentrations less than 1,000 $\mu$g/L. Thus, while soils at 15 feet below the ground surface were assumed treated or removed to the 1,000 $\mu$g/kg level, shallower soils were typically treated to lower levels. Approximately 6,000 cubic yards of soil were estimated to have been treated or removed for this alternative.

This alternative included the pumping of EW-2 at 320 gpm for 5 years. This is the assumed time period required to remove the groundwater contaminant plume. After 5 years, EW-2 was shut off without maintenance pumping. This alternative was evaluated for each of four vertical hydraulic conductivity values for the upper clay unit. The values ranged greater than two orders

of magnitude from 5 x $10^{-5}$ cm/sec to 1 x $10^{-7}$ cm/sec. The range of conductivity values were assumed to span any reasonable range of uncertainty in this type IV parameter.

The simulation with the vertical conductivity if the upper clay soil of 5 x $10^{-5}$ cm/sec resulted in no plume generation. Essentially all of the TCE contained in the soils was leached by the time the pump was turned off in five years. The maximum TCE concentration in water in the clay soil at five years (end of pumping) was 2 $\mu$g/L. This conductivity value is not realistic for these soils but it provides an upper limit for the TCE leaching and demonstrates that higher conductivities are not an issue for potential impact to the wellfield.

The simulation with a vertical conductivity of the upper clay soil of 1 x $10^{-5}$ cm/sec resulted in a small 5 $\mu$g/L plume after five years. The maximum extent of the plume was 90 feet from the source, within the property of the GSS. The maximum depth of the plume was 893 feet amsl, or 7 feet below the top of the aquifer. These values were for 10 years, or five years after pumping stopped. The maximum TCE concentration in water in the clay soil after 10 years was 40 $\mu$g/L. At 20 years, the maximum concentration was 16 $\mu$g/L, and at 30 years it was 6 $\mu$g/L.

The simulation with a vertical conductivity for the upper clay soils of 1 x $10^{-6}$ cm/sec resulted in no generation of a 5 $\mu$g/L plume. The maximum TCE concentration in water in the clay soils at 10 years was 140 $\mu$g/L. At 20 years the maximum was 100 $\mu$g/L, and at 30 years it was 80 $\mu$g/L.

The simulation with a vertical conductivity for the upper clay soils of 1 x $10^{-7}$ cm/sec also resulted in no plume generation. The maximum TCE concentrations remaining in the water in the clay soil were 180 $\mu$g/L after 10 years, 160 $\mu$g/L after 20 years, and 140 $\mu$g/L after 30 years.

A worst case model result for this alternative is a plume extending approximately 90 feet from the source. This is not an off-site plume, and the plume would have to expand approximately 15 times this distance to impact the nearest active well in the Granville wellfield (PW-2).

The affects of the potential presence of DNAPLs for this scenario are minimal. Treating all soils with TCE concentrations greater than 1,000 $\mu$g/kg should remove any potential source areas with DNAPLs. If DNAPLs were present in the clay soil they would be associated with high soil concentrations. Areas with high TCE concentration were identified in the soil investigation and would be treated as part of this alternative.

## 6.4 ALTERNATIVE 4 - SOIL REMEDIATION TO 5,000 $\mu$G/KG TCE

For this alternative, all clay soils with TCE concentrations greater than 5,000 $\mu$g/kg were assumed to have been removed by excavation or treated by other methods to remove the contaminant. When deeper soils were treated, the soils above them were also considered to be treated, even if the shallower soils had TCE concentrations less than 5,000 $\mu$g/kg. Thus, while soils, at 15 feet below the ground surface, were treated to the 5,000 $\mu$g/kg level, shallower soils were typically treated to levels closer to 1,000 $\mu$g/kg. About 3,000 cubic yards of soil were estimated to have been treated or removed.

This alternative also included the pumping of extraction well EW-2 at 320 gpm for 5 years. This is the assumed time period required to remove the contaminant plume from the aquifer. After 5 years, EW-2 was shut off without maintenance pumping. This alternative was evaluated at each of four vertical hydraulic conductivity values for the upper clay soils. The values ranged from $5 \times 10^{-5}$ cm/sec to $1 \times 10^{-7}$ cm/sec. The range in upper clay soil vertical conductivity values was assumed to cover any reasonable range of uncertainty in this type IV parameter.

The simulation with the vertical conductivity of the upper clay soil of $5 \times 10^{-5}$ cm/sec resulted in no plume generation. Essentially all of the TCE contained in the clay soils was removed by the time the pump was turned off after five years. The maximum TCE concentration in the pore water of the clay soils after five years was 5 $\mu$g/L. This high conductivity is probably not realistic for the clay soils, but it provides an upper limit for TCE leaching and demonstrates that higher conductivities are not an issue for potential impact to the wellfield.

The simulation of 1 x $10^{-5}$ cm/sec in the upper clay soils resulted in a small 5 $\mu$g/L plume after five years. The maximum extent of the plume was 280 feet from the soil source. This is beyond the property of the GSS. The maximum depth of the plume was 881 feet amsl, or 19 feet below the top of the aquifer. These maximum values were obtained at 10 years (or five years after the pumps had been turned off). The maximum TCE concentration in the clay soil pore water at 10 years was 100 $\mu$g/L. At 20 years, the maximum concentration was 35 $\mu$g/L, and at 30 years it was 12 $\mu$g/L. Thus, with this relatively high conductivity for the upper clay soils, a small plume was generated but the maximum extent of the plume was just beyond the property boundaries and the plume receded after 10 years.

The simulation with a vertical conductivity for the upper clay soils of 1 x $10^{-6}$ cm/sec resulted in no development of a 5 $\mu$g/L plume. The maximum TCE concentration in the clay soil pore water after 10 years was 200 $\mu$g/L. After 20 years the maximum was 180 $\mu$g/L, and after 30 years it was 140 $\mu$g/L.

The simulation with a vertical conductivity in the upper clay soils of 1 x $10^{-7}$ cm/sec (closest to the laboratory permeability values) also resulted in no plume generation. The maximum TCE concentrations remaining in the clay soil water were 450 $\mu$g/L after 10 years, 350 $\mu$g/L after 20 years, and 300 $\mu$g/L after 30 years.

A "worst case" model result for this alternative is a plume generation of approximately 280 feet from the contaminant source. This does represent an off-site plume, but it does not come close to impacting the Granville wellfield. The plume would have to extend to five times this distance to impact the nearest well in the wellfield (PW-2).

The affects of the potential presence of DNAPLs for this scenario are minimal. Treating the soil to a level of 5,000 $\mu$g/kg should remove any potential source areas with DNAPLs. The presence of DNAPLs in the clay soil would be associated with high concentration soils; these soils have been identified in the soil investigation and would be treated as part of this alternative.

## 6.5 ALTERNATIVES EVALUATION CONCLUSIONS

The model results for the four evaluated alternatives are summarized in Table 3. Of the four alternatives evaluated, only the no action alternative is unacceptable. This conclusion is based on evaluation of the alternatives using a calibrated groundwater flow model combined with a contaminant fate and transport model. The sensitivity of the model was thoroughly evaluated prior to simulating the alternative scenarios. The primary parameter with type IV sensitivity was the vertical hydraulic conductivity of the impacted upper clay soils. The uncertainty introduced by this parameter was carefully controlled as part of the simulation of alternatives.

The affects of potential residual DNAPLs in the upper clay soil were not directly evaluated by the model. However the potential presence of DNAPLs was evaluated qualitatively outside of the modeling effort for each alternative. It was determined that alternative 2 (maintenance pumping to year 20 with no active soil remediation) was relatively sensitive to potential DNAPLs, while alternatives 3 and 4 (TCE clean-up to 1,000 $\mu$g/kg and 5,000 $\mu$g/kg levels, respectively) are not likely to be sensitive to residual DNAPLs.

Comparing alternatives 3 and 4, there is no reason to choose to remediate the soils to the 1,000 $\mu$g/L levels rather than 5,000 $\mu$g/L. Part of the reason for this is that some clay soil with TCE concentrations less than 5,000 $\mu$g/L would have to be treated or removed in the process of treating or removing 5,000 $\mu$g/kg clay soils at depth. Soils in the upper five feet would be effectively treated to levels of 1,000 $\mu$g/kg. Overall, the additional removal or treatment of 3,000 cubic yards of soil to go from alternative 3 to alternative 4 does not seem to be justified.

## 7.0 SUMMARY

1. The groundwater flow model combined with the contaminant fate and transport model was used in evaluating four alternative scenarios for the remediation of impacted soils and groundwater at the GSS. The flow model was calibrated based on a 98-hour pumping test conducted at the GSS in 1995. Calibration of the fate and transport model was not possible. A sensitivity analysis was conducted on the combined model to help determine what level of confidence should be placed in the results and to identify those parameters which could contribute to errors in the conclusions.

2. The primary parameter producing the greatest potential for error in the model is the vertical conductivity of the impacted upper clay soils. This parameter was systematically and carefully evaluated in each scenario to minimize the effects of uncertainty on the conclusions provided by the model.

3. The four alternatives evaluated were: (1) no action, (2) maintenance pumping for 15 years following 5 years of aggressive pumping, (3) soil treatment or removal to 1,000 $\mu$g/kg coupled with five years of aggressive pumping, and (4) soil treatment or removal for all soils with TCE greater than 5,000 $\mu$g/kg, including five years of aggressive pumping. All but the no action alternative provide acceptable outcomes.

4. The potential presence of DNAPLs was evaluated outside the model for each of the scenarios. This provided a means of better differentiating the risks of DNAPL affecting the results for each alternative. Removal of TCE from soils exceeding 5,000 $\mu$g/kg would remove DNAPLs if they were present. Removal of TCE from soils exceeding 1,000 $\mu$g/kg TCE also would remove DNAPL if they were present. Results from alternative 2 would probably be affected the greatest by the potential presence of DNAPLs. For the no action alternative, the wellfield would be impacted with or without DNAPLs, but the level of impact on the wellfield under alternative 1 would increase if DNAPLs were present.

5. Alternatives 3 and 4 have acceptable results. The risk of plume regeneration with or without the presence of DNAPL is slightly higher under alternative 4 than alternative 3.

6. The modeling results presented in this report are useful for comparing alternative strategies for soil and groundwater clean-up. They should not be used to provide specific information regarding timing of clean-up activities or distances of plume migration. The uncertainty in this modeling effort has been handled by either using conservative assumptions with respect to potential wellfield impact or carefully analyzing the effects of the uncertainty and developing a "worst case" scenario for those parameters critical to model predictions. The conclusions, based on model results, are valid for comparative purposes among the alternative remediation strategies. The EE/CA, currently being prepared, will examine the remedial alternatives and select one.

## 8.0 REFERENCES


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# TABLES

# TABLE 1
# MODEL PARAMETERS BY LAYER

| Model Layer | Layer Thickness (feet) | Horizontal Hydraulic Conductivity (ft/day) | Vertical Hydraulic Conductivity (ft/day) | Storativity | Specific Yield | Porosity | Longitudinal Dispersivity (feet) | Lateral Dispersivity (feet) | Vertical Dispersivity (feet) | First Order Rate Constant (1/day) | Dry Bulk Density (kg/cubic ft.) | Sorption Coefficient (ft^3/kg)) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0.00028 | 0.00028 | 0.001 | 0.02 | 0.35 | 10 | 1 | 1 | 0 | 58.2 | 0.0428 |
| 2 | 5 | 0.00028 | 0.00028 | 0.001 | 0.02 | 0.35 | 10 | 1 | 1 | 0 | 58.2 | 0.0428 |
| 3 | 5 | 0.00028 | 0.00028 | 0.001 | 0.02 | 0.35 | 10 | 1 | 1 | 0 | 58.2 | 0.0428 |
| 4 | 5 | 0.00028 | 0.00028 | 0.001 | 0.02 | 0.35 | 10 | 1 | 1 | 0 | 58.2 | 0.0428 |
| 5 | 5 | 0.00028 | 0.00028 | 0.001 | 0.02 | 0.35 | 10 | 1 | 1 | 0 | 58.2 | 0.0428 |
| 6 | 8 | 170 | 17 | 0.00013 | 0.12 | 0.3 | 10 | 1 | 0.1 | 0 | 56.5 | 0.00268 |
| 7 | 8 | 170 | 17 | 0.00013 | 0.12 | 0.3 | 10 | 1 | 0.1 | 0 | 56.5 | 0.00268 |
| 8 | 20 | 170 | 17 | 0.00013 | 0.12 | 0.3 | 10 | 1 | 0.1 | 0 | 56.5 | 0.00268 |
| 9 | 24 | 250 | 25 | 0.00013 | 0.12 | 0.3 | 10 | 1 | 0.1 | 0 | 56.5 | 0.00268 |
| 10 | varies | 250 | 25 | 0.00013 | 0.12 | 0.3 | 10 | 1 | 0.1 | 0 | 56.5 | 0.00268 |

# TABLE 2
## SUMMARY OF SENSITIVITY ANALYSIS

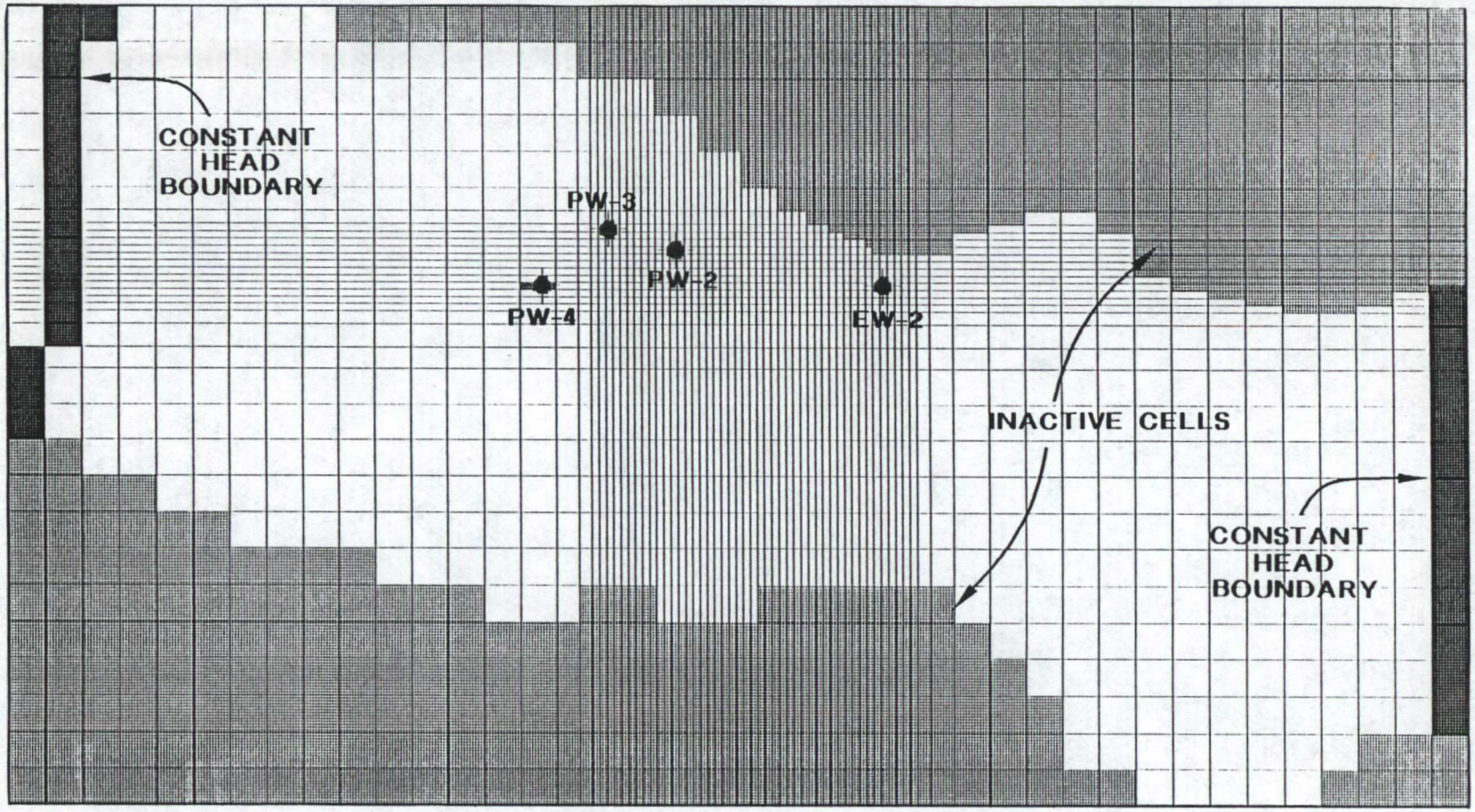
| Parameter | Varied in Which Layers | Parameter Multiplier* | Maximum Distance of Lateral Spread (ft) | Time of Maximum Lateral Spread (years after pump is off) | Change to Calibration | Change to Model Conclusions | Type of Sensitivity |
|---|---|---|---|---|---|---|---|
| Base Model Used for Sensitivity Analysis | NA | NA | 541 | NA | NA | NA | NA |
| Degradation Constant | 1-10 | (s)=0.0002 (ns)=0.00002 | 485 | 5 | none | insignificant | type I |
| Longitudinal Dispersivity | 1-10 | 0.2X | 668 | 5 | none | insignificant | type I |
| Molecular Diffusion | 1-10 | 10X | 580 | 8 | none | insignificant | type I |
| Molecular Diffusion | 1-10 | 100X | 537 | 5 | none | insignificant | type I |
| Porosity (aquifer) | 6-10 | 1.17X | 577 | 5 | insignificant | insignificant | type I |
| Porosity (aquifer) | 6-10 | 0.83X | 556 | 5 | insignificant | insignificant | type I |
| Sorption Constant | 1-10 | 5X | 653 | 15 | none | insignificant | type I |
| Sorption Constant | 1-10 | 0.2X | 347 | 5 | none | insignificant | type I |
| Specific Yield (aquifer) | 6-10 | 1.5X | 527 | 5 | insignificant | insignificant | type I |
| Specific Yield (aquifer) | 6-10 | 0.5X | 666 | 10 | insignificant | insignificant | type I |
| Storativity (aquifer) | 6-10 | 0.1X | 665 | 10 | significant | insignificant | type II |
| Storativity (aquifer) | 6-10 | 10X | 666 | 10 | significant | insignificant | type II |
| Horizontal Hydraulic Conductivity (aquifer) | 6-10 | 2X | 1519 | 10 | significant | significant | type III |
| Horizontal Hydraulic Conductivity (aquifer) | 6-10 | 0.75X | model unstable due to dewatering | | significant | significant | type III |
| Vertical Hydraulic Conductivity (aquifer) | 6-10 | 0.1X | 866 | 10 | significant | significant | type III |
| Vertical Hydraulic Conductivity (aquifer) | 6-10 | 10X | 821 | 10 | significant | significant | type III |
| Degradation Constant | 1-10 | (s)=0.002 (ns)=0.0002 | 218 | 5 | none | significant | type IV |
| Longitudinal Dispersivity | 1-10 | 5X | 250 | 2 | none | significant | type IV |
| Vertical Hydraulic Conductivity (clay) | 1-5 | 0.01X | 102 | 5 | insignificant | significant | type IV |
| Vertical Hydraulic Conductivity (clay) | 1-5 | 0.1X | 235 | 5 | insignificant | significant | type IV |
| Vertical Hydraulic Conductivity (clay) | 1-5 | 2X | 374 | 5 | insignificant | significant | type IV |

*degradation constants are provided rather than a multiplier for sorbed (s) and non-sorbed (ns)conditions.. The calibrated model contained no degradation constant (units are L/day).

## TABLE 3
## SUMMARY OF MODEL RESULTS FOR EVALUATED ALTERNATIVES

| Alternative | Worst Case Lateral Plume Migration (feet) | Deepest Penetration of Contaminants into Aquifer (feet) | Maximum Soil TCE Concentration at 20 years (ug/kg) | Wellfield Impact |
|---|---|---|---|---|
| 1. No Action | >2000 | Bedrock | 200 | yes |
| 2. Long Term Pumping | 125 | 15 | 200 | no |
| 3. Soil Removal/Treatment to 1000 ug/L | 90 | 7 | 16 | no |
| 4. Soil Removal/Treatment to 5000 ug/L | 280 | 19 | 35 | no |

# FIGURES

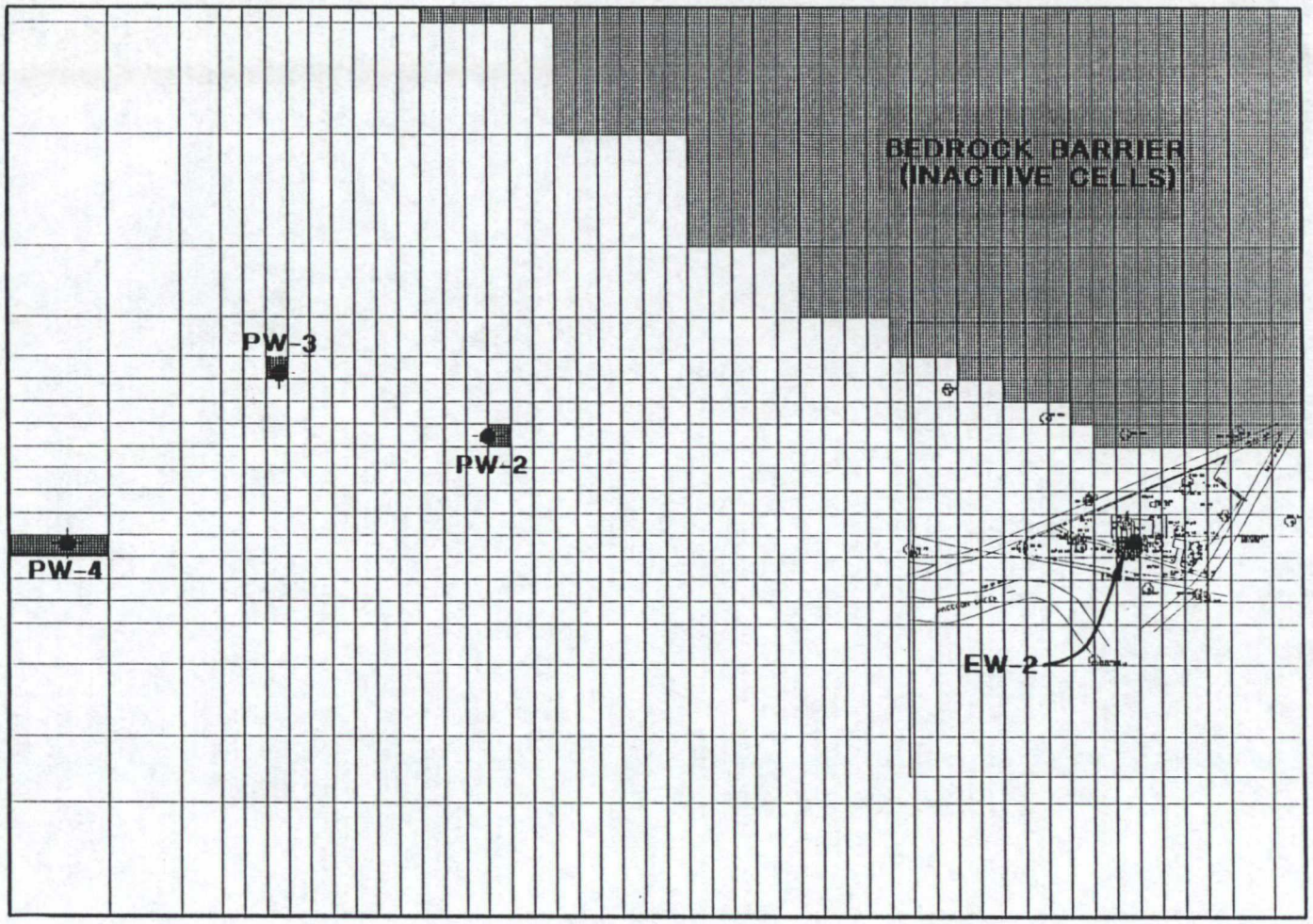



M&E

**Modeled Region with Grid, Inactive Cells and Constant Head Cells**
**Granville Solvents Site**
**Granville, Ohio**

**Project Number**
**016688-0008-300**

**Figure 1**

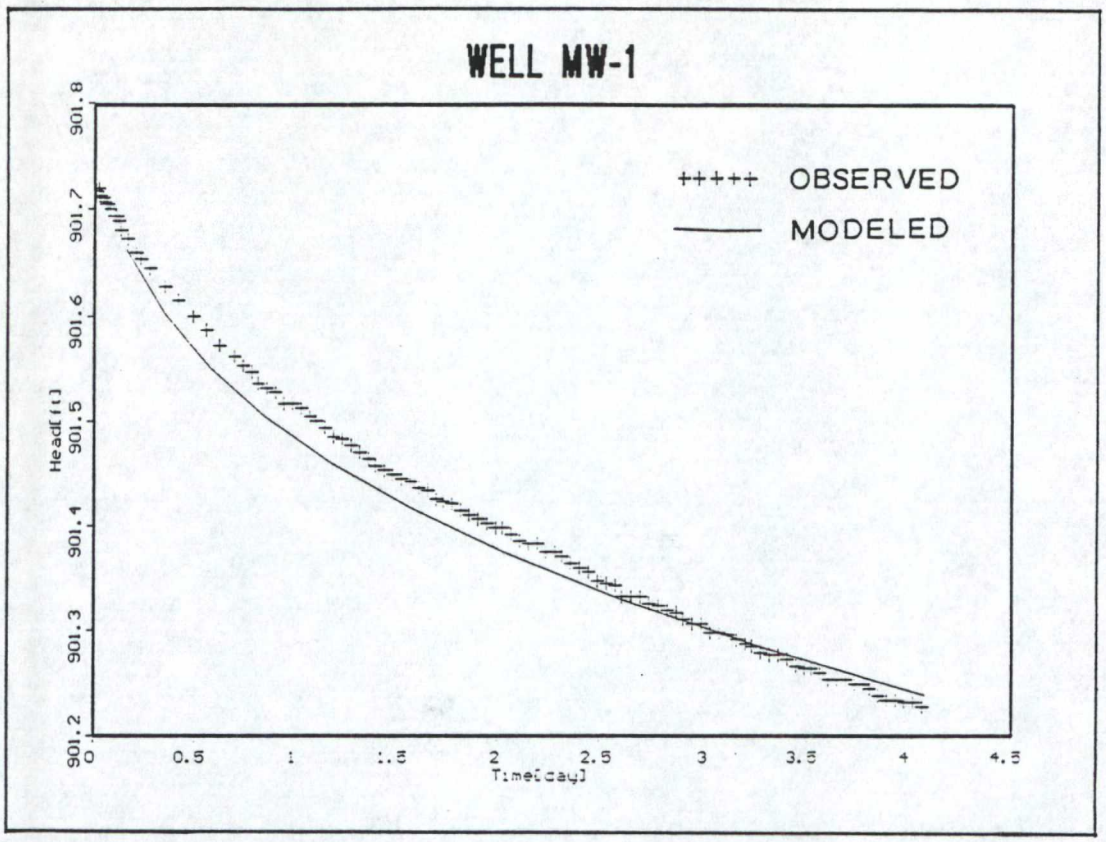


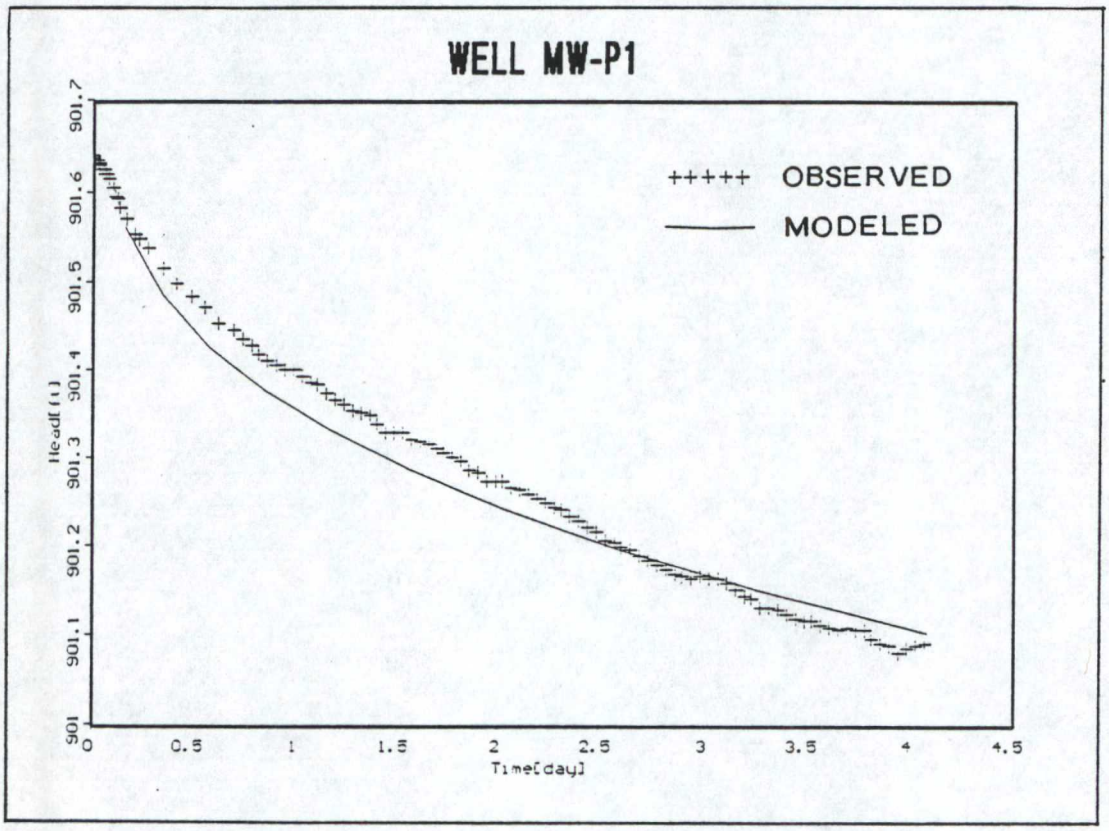

M&E

**Enlargement of Grid in Area of Wellfield and the GSS**
**Granville Solvents Site**
**Granville, Ohio**

**Project Number**
**016688-0008-300**

**Figure 2**



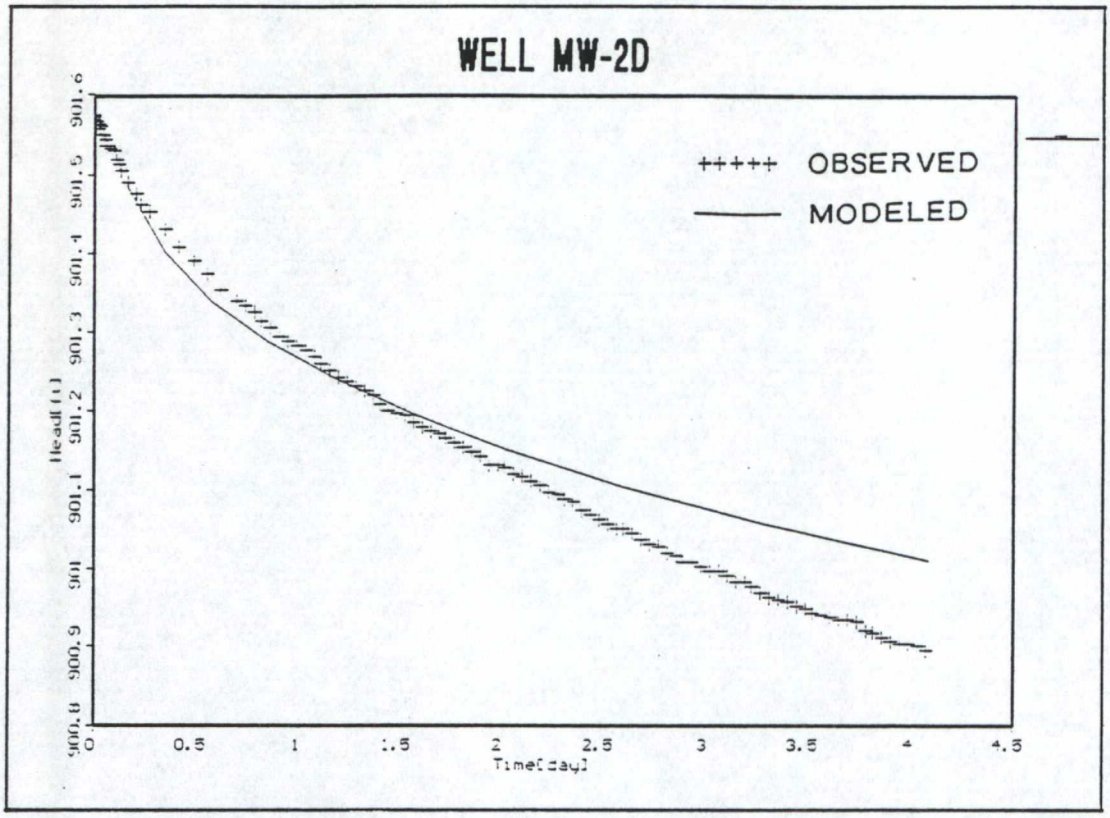



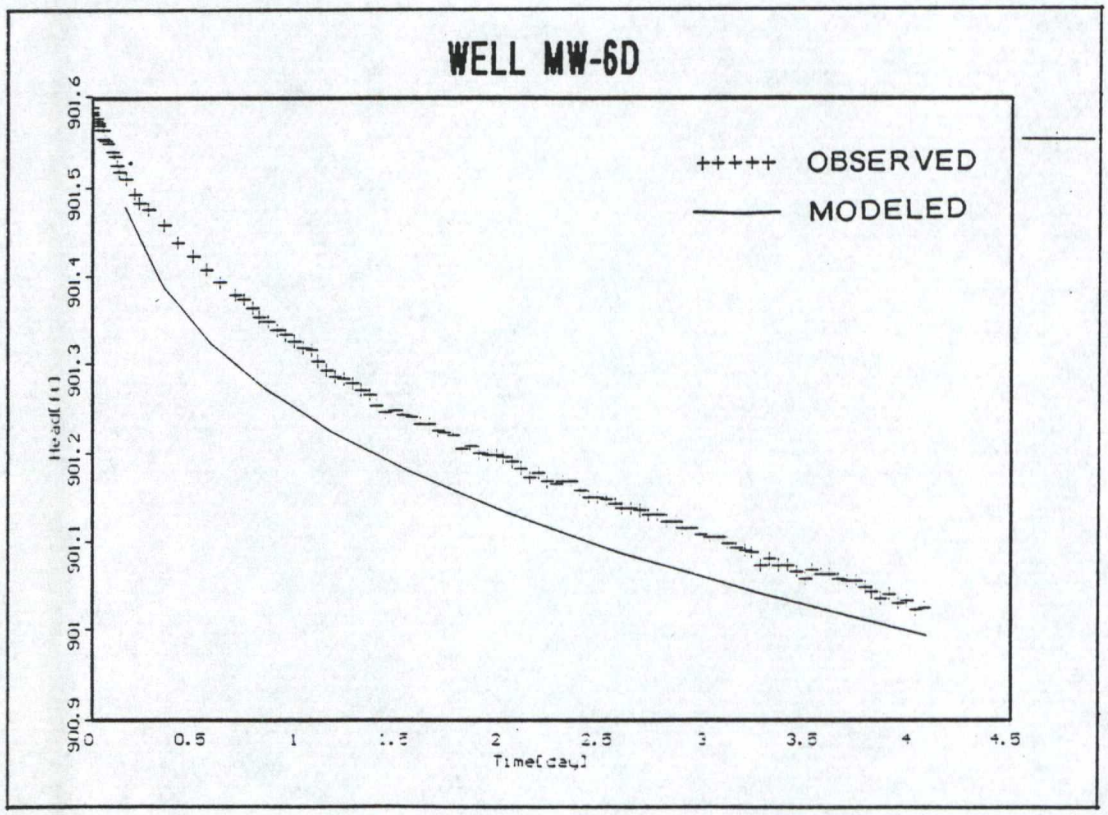

M&E

**Observed vs. Modeled for 98 Hour Pumping Test, Wells MW-1 and MW-P1**
**Granville Solvents Site**
**Granville, Ohio**

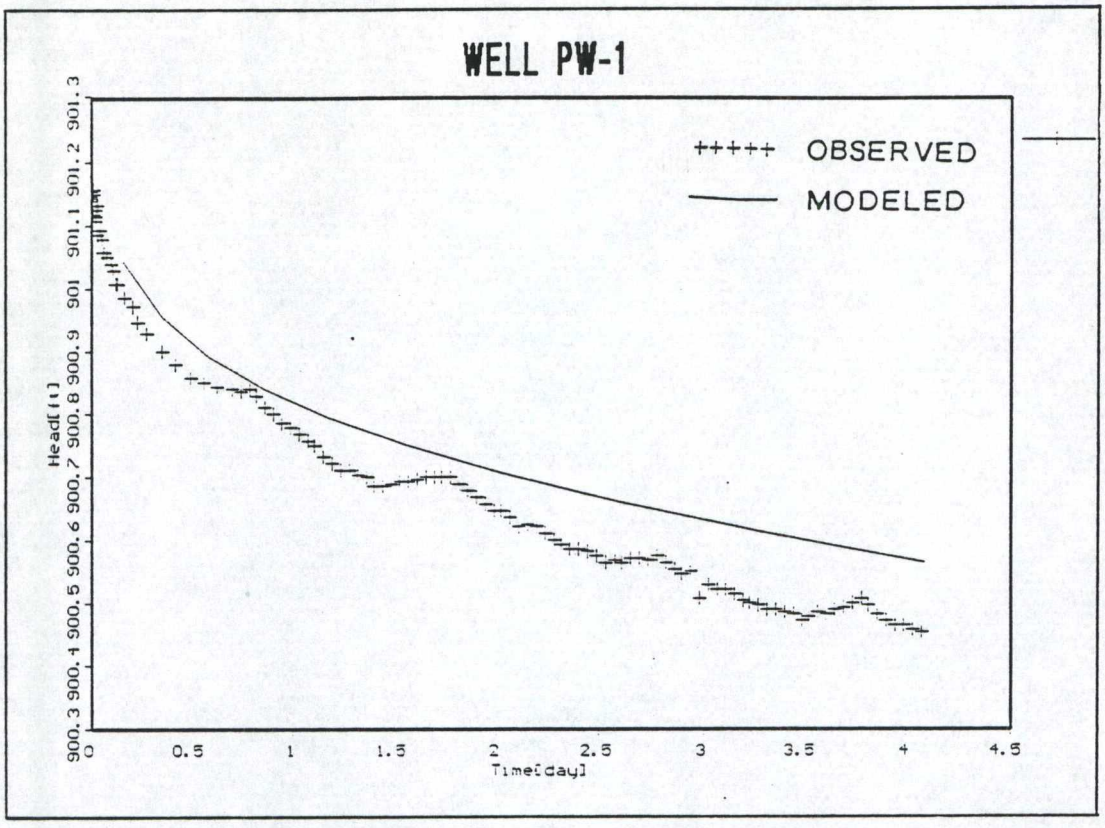
**Project Number**
**016688-0008-300**

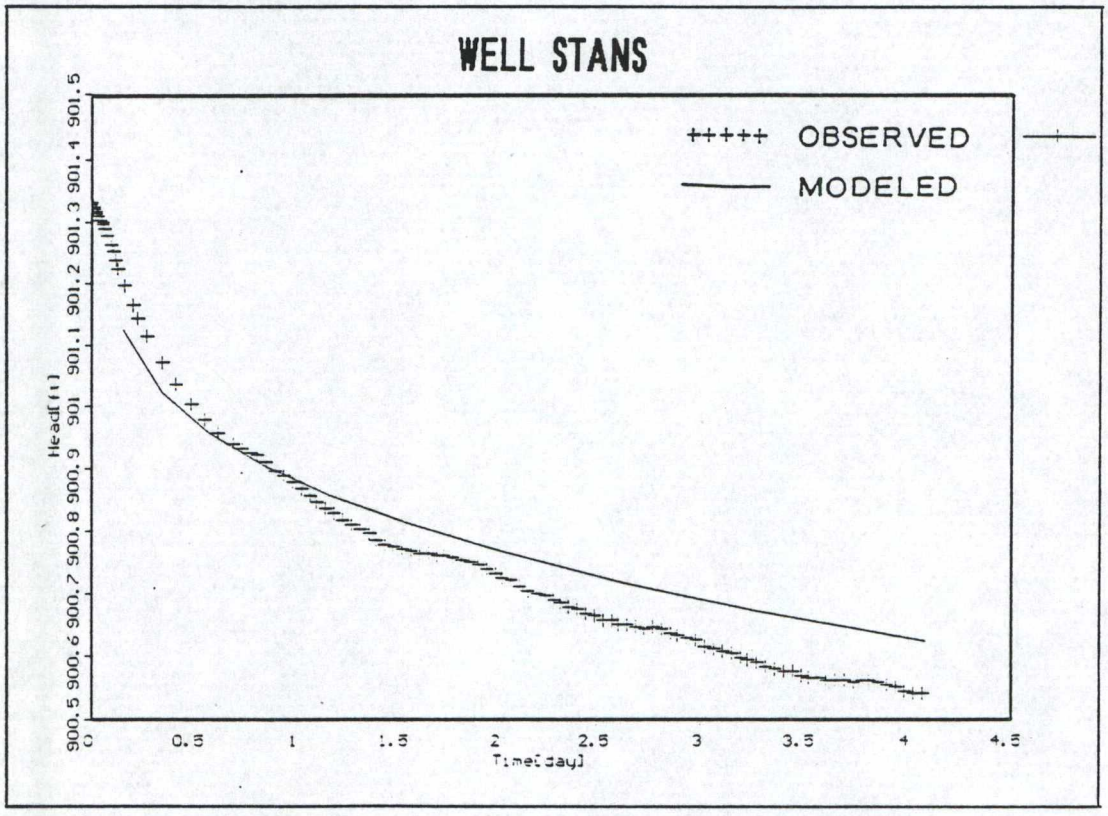
**Figure 3**



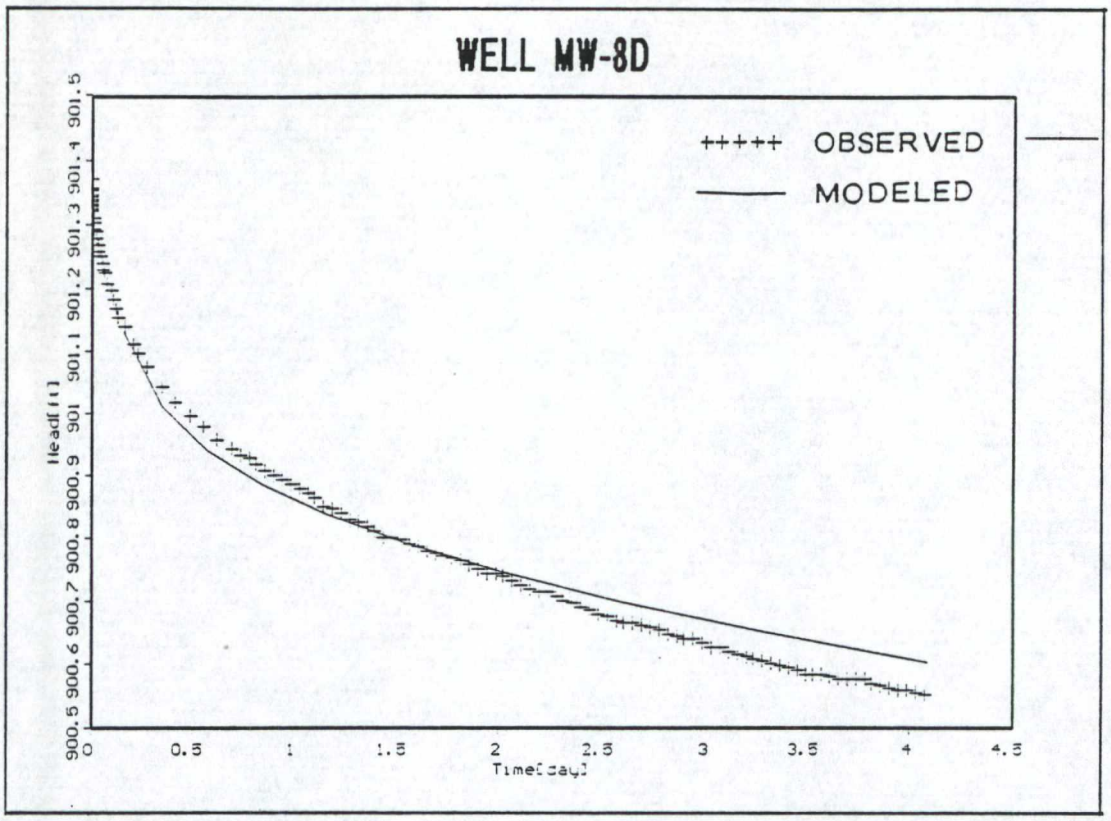



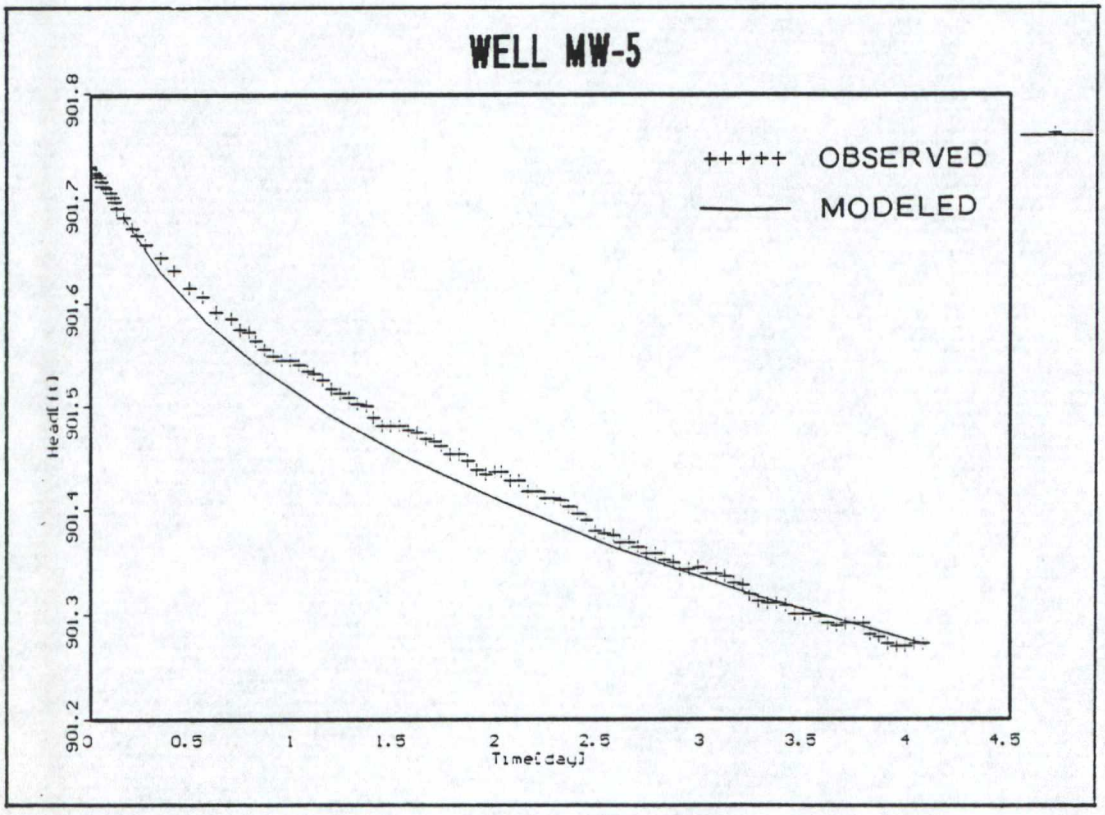

| | | |
|---|---|---|
| M&E | **Observed vs. Modeled for 98 Hour Pumping Test, Wells MW-2D and MW-6D Granville Solvents Site Granville, Ohio** | **Project Number 016688-0008-300** |
| | | **Figure 4** |




| | | |
|---|---|---|
| M&E | **Observed vs. Modeled for 98 Hour Pumping Test, Wells PW-1 and STANS**<br>**Granville Solvents Site**<br>**Granville, Ohio** | **Project Number**<br>**016688-0008-300**<br><br>**Figure 5** |



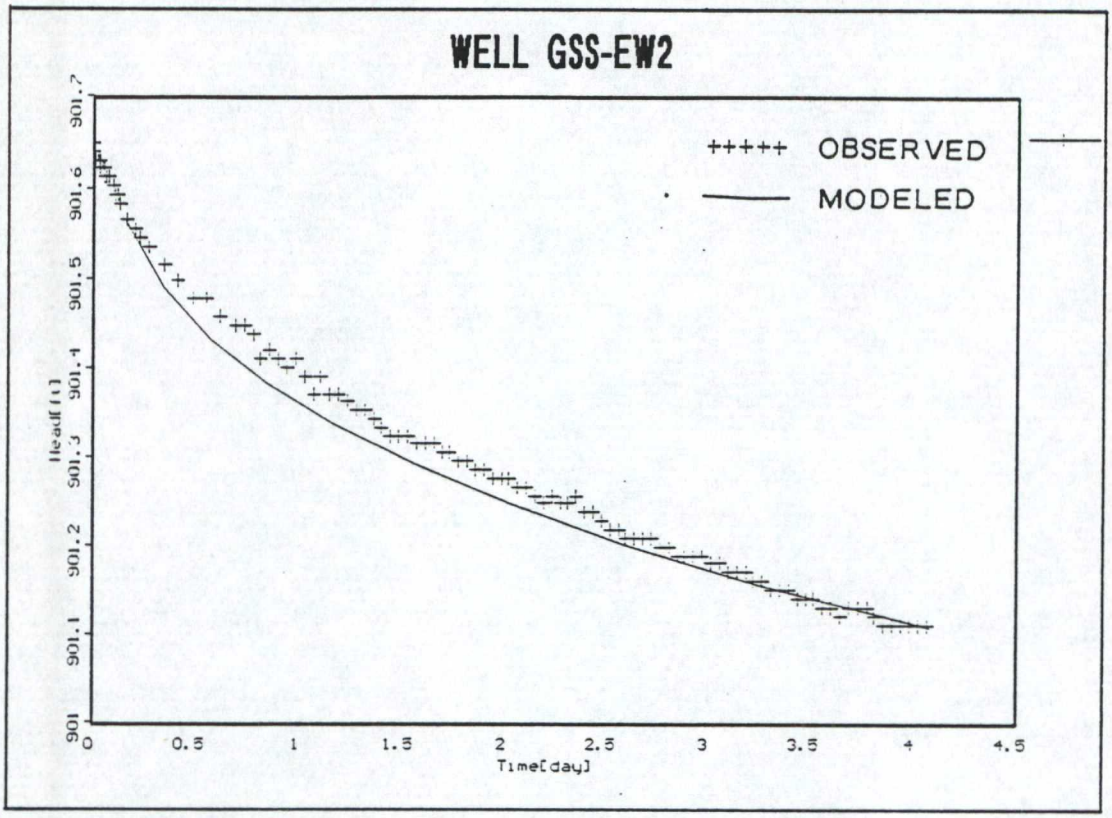




M&E

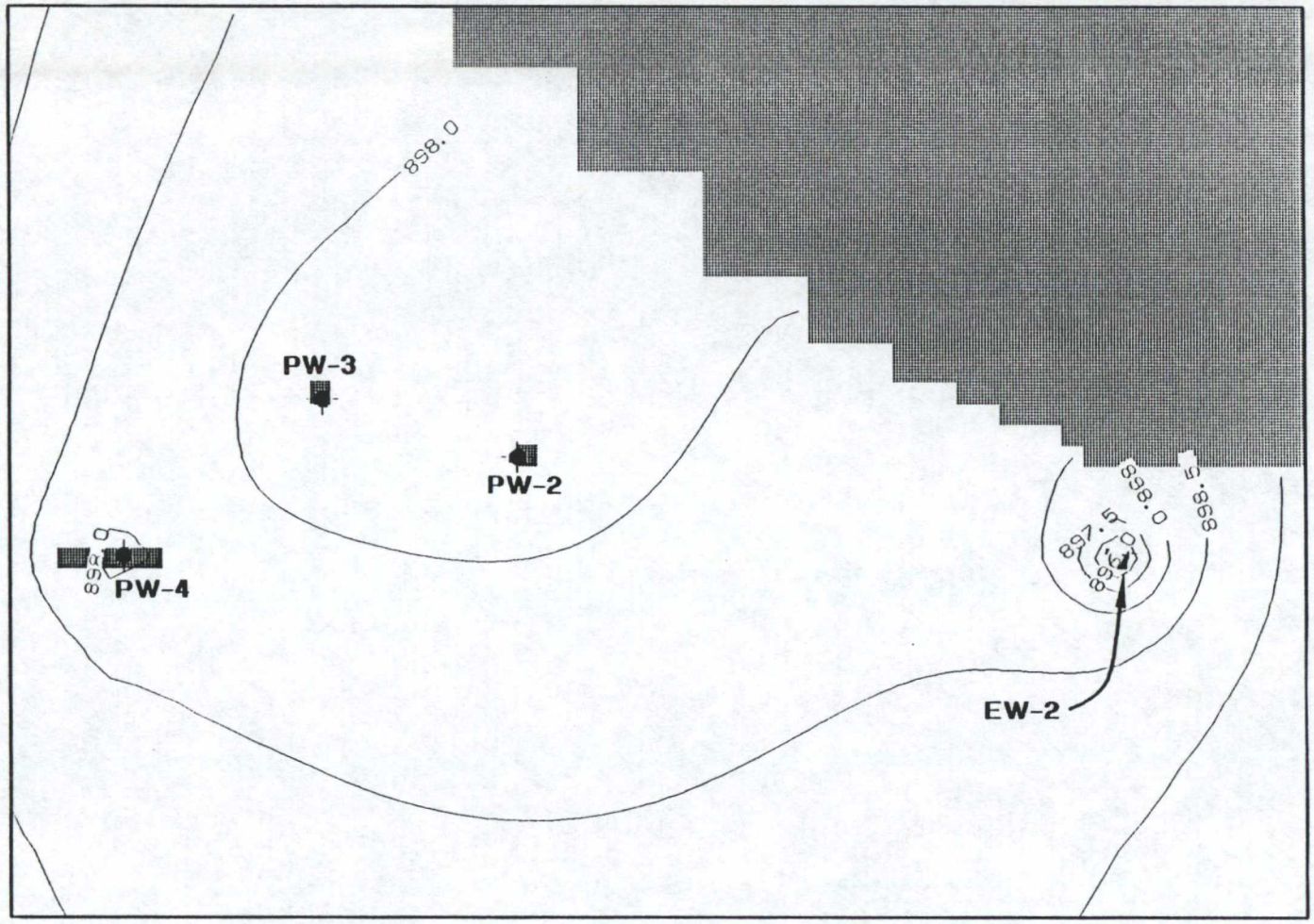
**Observed vs. Modeled for 98 Hour Pumping Test, Wells MW-8D and MW-5**
**Granville Solvents Site**
**Granville, Ohio**

**Project Number**
**016688-0008-300**

**Figure 6**




| | | |
|---|---|---|
| M&E | **Observed vs. Modeled for 98 Hour Pumping Test, Well GSS-EW2 Granville Solvents Site Granville, Ohio** | **Project Number 016688-0008-300** |
| | | **Figure 7** |

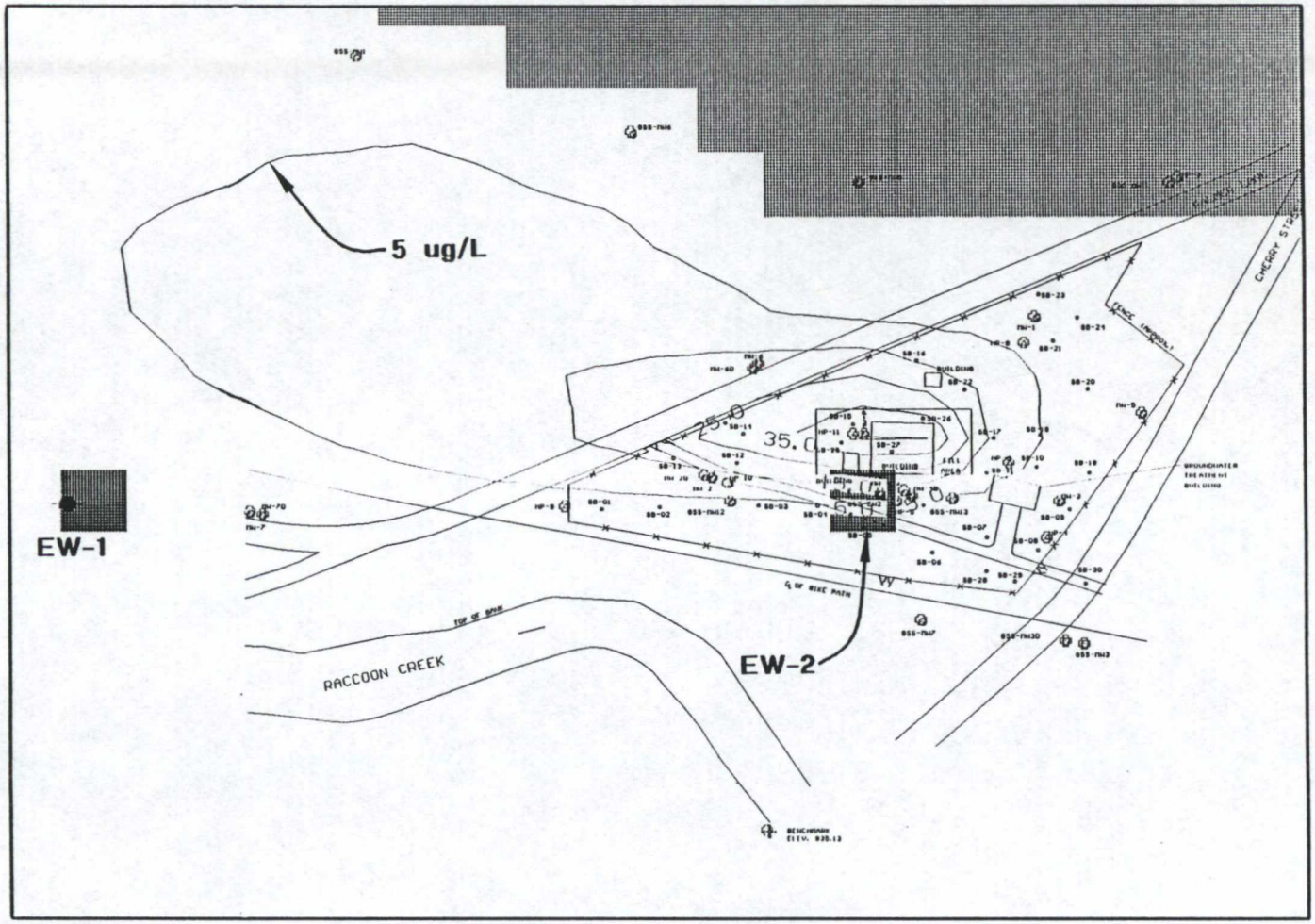



M&E

**Steady State Potentiometric Surface**
**for Base Model of Sensitivity Analysis**
**Granville Solvents Site**
**Granville, Ohio**

**Project Number**
**016688-0008-300**

**Figure 8**




M&E

**Maximum Extent of 5μg/L TCE Plume for Base Model of Sensitivity Analysis**
**Granville Solvents Site**
**Granville, Ohio**

**Project Number**
**016688-0008-300**

**Figure 9**

# APPENDIX A

Metcalf & Eddy
An Air & Water Technologies Company

September 11, 1996

Ms. Diane Spencer, Project Coordinator
U.S. Environmental Protection Agency, Region 5
Office of Superfund, Remedial & Enforcement Response Branch
77 West Jackson Boulevard
Chicago, Illinois 60604-3590

Subject: **Granville Solvents Site Removal Action**
**Transmittal: Description of the Fate and Transport Modeling**

Dear Ms. Spencer:

Attached is a letter describing the methodology of the Fate and Transport Modeling for the site soils. The Soil Data Report was sent to you yesterday, September 10, 1996 with a transmittal letter carrying the incorrect submittal date of September 5, 1996. We hope that this does not cause you any inconvenience.

Early next week we will provide you with a copy of the Meeting Agenda and Schedule along with directions from the airport to the M&E office here in Columbus. If you have questions, please call Michael Raimonde or me at 614-890-5501.

Respectfully,

METCALF & EDDY OF OHIO, INC.

Michael A. Raimonde for

Gerald R. Myers
Vice President/Project Coordinator

Attachment

cc: B. Pfefferle, TH&F
M. Anastasio, U.S. EPA
F. Myers, Ohio EPA
D. Plunkett, Granville
M. Raimonde, M&E

2800 Corporate Exchange Drive, Suite 250, Columbus, OH 43231
TEL: 614-890-5501 FAX: 614-890-7421

Metcalf & Eddy
An Air & Water Technologies Company

September 11. 1996

Ms. Diane Spencer, Project Coordinator
U.S. Environmental Protection Agency, Region 5
Office of Superfund. Remedial & Enforcement Response Branch
77 West Jackson Boulevard
Chicago, Illinois 60604-3590

Subject: **Granville Solvents Site Removal Action**
**Description of the Fate and Transport Modeling**

Dear Ms. Spencer:

Following is a discussion of the methodology of the modeling effort to determine what impacted soil must be remedied to achieve protection of the groundwater. This discussion is divided into four parts: Purpose Statement, Modeling Software, Model Set-up, and Model Use. We expect to have results of this effort ready for discussion in the scheduled meeting on Wednesday, September 25, 1996.

## Purpose Statement

The Preliminary Remedial Goals (PRGs) established in the Design Technical Memorandum (DTM) for the site were based on maximum contaminant levels in groundwater and assumed dilution and attenuation factors. Now that more data are available for the aquifer and the overlying soils, a more detailed effort is warranted to provide site specific remedial goals for the soils and develop remediation strategies. A groundwater fate and transport model will be used to meet this objective.

## Modeling Software

| | |
|---|---|
| Flow model: | MODFLOW / MODPATH (USGS, 1988 / 1989) |
| Fate and Transport Model: | MT3D v. 1.86 (Papadopulos, 1995) |

2800 Corporate Exchange Drive, Suite 250, Columbus, OH 43231
TEL: 614-890-5501 FAX: 614-890-7421

## Model Set-up

The flow model will be set up in a simplified manner to approximate the conditions observed in the aquifer and the overlying soils. The boundary conditions for the numerical flow model will be chosen to approximate the buried valley conditions and the gradient applied to the aquifer by pumping of the Village of Granville Wellfield. No-flow boundaries will be used to represent valley walls in the model and constant head boundaries will be used to simulate the background aquifer gradient. The clay-rich soils overlying the aquifer will also be simulated in the model. These soils have been found to be saturated (19% pre- and post-flexible wall permeability test) and will be modeled using constant head cells to maintain groundwater recharge through the clay and into the aquifer. No flow boundaries will be used at the perimeter of the clay-rich soil layers.

The aquifer characteristics used in the model will be derived from pumping tests conducted at the site. Where necessary, characteristics will be assumed based on similarities between this aquifer system and other similar aquifer systems in Ohio. The organic carbon content of the soil will be established based on total organic carbon (TOC) analyses conducted using site samples. The model layers will be chosen to represent breaks in the soil stratigraphy determined from boring logs.

The characteristics of the overlying soils will be based on the analytical results of soil samples provided in the Data Report for the DTM. These data include vertical permeability measurements from a variety of locations, TOC values from several locations, and moisture content analyses from a variety of locations. Characteristics of off-site soils will be assumed similar to the on-site soils.

Initial contaminant concentrations in the aquifer will be based on the concentrations observed at the time of the Hydropunch study (1994). The contaminant concentration in the soils will be established based on data from the recent soil sampling program. Model layers in the clay-rich soils will be chosen to better establish soil contaminant concentrations through the soil profile.

The groundwater flow model will be calibrated based on pumping test data and the observed potentiometric surfaces at the site. Attention will be given to contaminant concentrations in the model calibration procedure. However, the dates and methods of contaminant release are not known and an accurate model calibration based on contaminant transport will not be reasonably possible.

## Model Use

The model will be used to predict the time required to remove the current dissolved plume of contaminants in the aquifer under a variety of pumping strategies. The model will also be used to estimate the rate of contaminant recruitment from the overlying soils and to establish how this recruitment will affect groundwater contaminant concentrations.

Based on potentiometric surfaces created for the site over the operating history of the extraction system, it has been established that all contaminated groundwater is currently being captured by the pumping system. All of the area where soil contamination is present is within the capture zone of the pumping system, and the soil contamination area represents only a small portion of the area captured by the pumping system (as shown by site potentiometric surfaces). Therefore, as long as the pumping system is active, recruitment of contaminants to the aquifer from the overlying soils will not degrade groundwater quality. The recruited contaminants are rapidly captured by the pumping system.

However, after the pumping system has removed the dissolved phase of contaminants from the aquifer, it may be desirable to shut the pumping system off. One of the primary purposes of this modeling effort will be to determine the rate of recruitment of contaminants to the aquifer from the soil following the shut-down of the pumping system under a variety of soil remediation scenarios. In this manner, it will be possible to estimate the degree of soil remediation effort that will be required to prevent contamination of the aquifer system above the maximum contaminant levels (MCLs). Remedial goals for the soil will then be established based on the results of the modeling project. Ultimately, the validity of the model results will be determined from groundwater monitoring data following the shut-down of the pumping system. If conditions indicate the continued contamination of the aquifer from the soils, pumping will be resumed.

If you have questions regarding this submittal, please contact Michael Raimonde or me at (614) 890-5501.

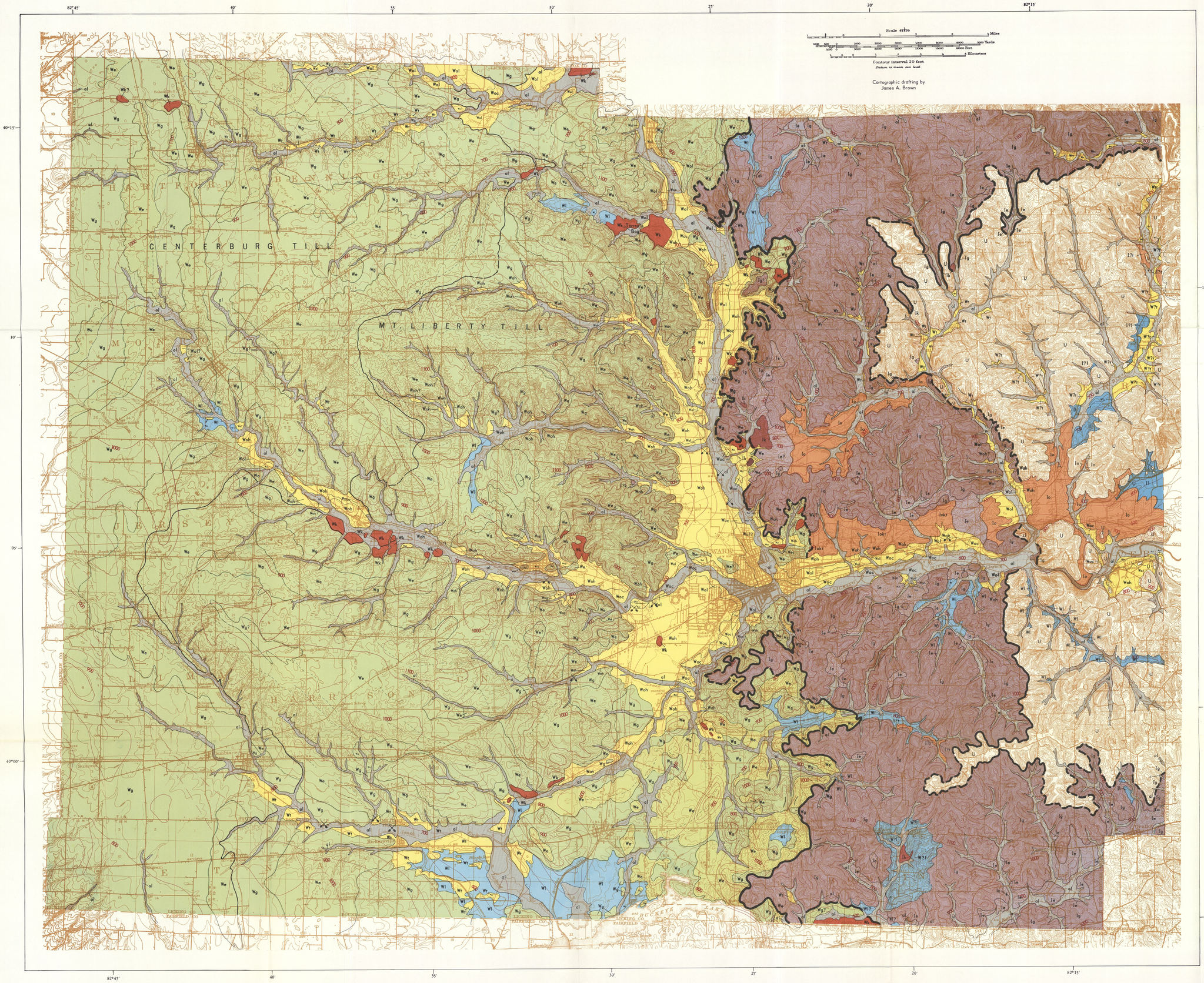
Respectfully,

METCALF & EDDY OF OHIO, INC.

Michael L. Raimonde for

Gerald R. Myers
Vice President/Project Coordinator

cc: B. Pfefferle, TH&F
M. Anastasio, U.S. EPA
F. Myers, Ohio EPA
D. Plunkett, Granville
M. Raimonde, M&E




## EXPLANATION

### RECENT

al — Stream alluvium

### PLEISTOCENE

#### WISCONSIN

Wl — Lake deposits

Wog, Woh, Wol, Woc, Wt, Wtr — Outwash terraces
- Wog - Granville Terrace
- Woh - Vanatta Terrace (high terrace)
- Wol - Utica Terrace (low terrace)
- Woc - low-level cut terrace
- Wt - undifferentiated Wisconsin terrace
- Wtr - terrace cut into rock

Wk — Kames

We — End moraines

Wg — Ground moraine

#### ILLINOIAN

Il — Lake deposits

Io, It, Iokt — Io - outwash terrace
- Iokt - local kame terrace
- It - undifferentiated Illinoian terrace

Ik — Kames

Ie — End moraines

Ig — Ground moraine

### SYMBOLS

U — Unglaciated areas

Crestlines of end moraines

Line marking boundary of Wisconsin or Illinoian deposits

Line marking soil boundary within area of Wisconsin deposits

Position of pre-Wisconsin or pre-Illinoian divide

700 — Contours drawn on bedrock surface. Contour interval 100 feet

Gravel pit

## GLACIAL GEOLOGY

Licking County is located in central Ohio, just east of Columbus. Newark is the county seat. The county is drained by the Newark River and its tributaries, which flow eastward into the Muskingum drainage.

Glacial deposits are present throughout most of the county. These deposits are of both Wisconsin and Illinoian age and were formed along the east edge of the Scioto Lobe of the glacier. As a result, both glacial boundaries are oriented north-south, with the unglaciated portion of the county to the east. Deposits of sand and gravel form kame hills (fillings of glacial crevasses) and flat-topped outwash terraces (gravel washed out beyond the glacial margin). Local silt deposits, representing lacustrine or slack-water accumulations, are present. Glacial till composes broad, smooth-surfaced ground moraine and hummocky belts of end moraine, each belt identifying a separate retreatal position of the glacial margin. Because of the high bedrock hills of central and eastern Licking County, end moraines there are strongly arcuate and the glacial cover is generally quite thin. In such areas, the distinction between end moraine and bedrock hills is commonly difficult to make; the most useful basis for separation was found to be the presence of hummocky constructional topography.

### TILLS

The distinction between the Wisconsin and Illinoian tills is based on their distribution and the nature of the soils developed in them. Wisconsin till soils generally belong to the Alexandria group of soils and are 2 to 5 feet deep; Illinoian till soils are generally in the Fallsburg group and are 6 to 7 feet deep. In the southern part of Licking Township, just northeast of Buckeye Lake, there are some soils which, though they are 6 to 7 feet deep, look much more like deeper, more weathered Alexandria soils. It is possible that the till in which these soils were developed is "early" Wisconsin and might correlate with the Knox Lake Till of Knox County (Forsyth, 1961), but because no soils break was observed east of this area and because all previous workers were both caused by the same thick deposit of end moraine and kames in southeastern Washington Township. The deep narrow valley of Claylick Creek, 3 miles southeast of Newark, was created when ice blocked a west-flowing stream in the valley at Fleatown. Quarry Run, just east of Jacksontown, was diverted from its original westward flow by the outermost Wisconsin end moraine. Three miles north of Granville, Dry Run, which once flowed to the southwest, up the valley of Griffin Run, now drains eastward through the bedrock hills into the Licking River.

### BEDROCK SURFACE

The contour lines drawn on the buried bedrock surface reveal an integrated preglacial system of valleys, which drained to the southwest. These are interpreted to be part of the preglacial Teays drainage system. A major tributary of the Teays, the Groveport River, flowed south from Utica to Buckeye Lake. At Newark, the Groveport River was joined by a major tributary from the east, the Cambridge River. A third tributary, less clearly defined by the contour lines, flowed south from Johnstown to Pataskala and joined the Groveport River south of Hebron. Smaller tributaries were present in the valleys of Wilkins Run, Wakatomika Creek, and Lake Fork.

In places, there appears to be evidence for a few streams that were incised more deeply than the others and which seem to have flowed toward the east. These are interpreted to represent the first valleys resulting from diversions created by the initial glacial advance; the deeper cutting of these valleys would be explained by the abundant meltwater provided by the glacier. Since surficial evidence does not seem to support the existence of a pre-Illinoian glacier in this part of Ohio, these diversions were probably produced by the Illinoian ice.

These preglacial valleys were filled to a considerable depth by glacial materials. Maximum depths now recorded are in the main Groveport River valley east and south of Newark, where more than 400 feet of drift are measured in some places.

### MINERAL RESOURCES

The most important mineral resource among the glacial materials of Licking County is sand and gravel. There are more than a dozen active or recently active gravel pits in the county. Almost all of these pits are in the Vanatta Terrace which, despite a silt cap of 2 to 3 feet, appears to contain a better quality of gravel than is found in the lower terraces. The gravel that occurs in this terrace east of Granville is generally of poorer quality than that to the west, apparently because of the larger amounts of deleterious shale and friable sandstone present in it, presumably derived from the adjacent bedrock hills.

Peat is excavated from time to time in the area of Wisconsin lacustrine deposits 2 miles northeast of St. Louisville.

Ground water occurs in relatively abundant amounts in the gravels filling the deep buried valleys and also in minor amounts throughout the glaciated part of the county (Dove, 1960). Also significant among the county's natural resources are the richly productive soils developed in the glacial tills of western Licking County.

### DRAINAGE DIVERSONS

Wisconsin and Illinoian glaciers created drainage diversions. Striking diversions made by the Illinoian ice occur in the valleys of Wakatomika Creek, in eastern Perry Township and in northern Fallsbury Township. In addition, major Illinoian diversions took place in the valleys of Rocky Fork just south of Hickman and of Wilkins Run in southeastern Newton Township. Jonathan Creek, located along the Fairfield-Perry County line, was believed by Flint (1951, p. 6) to have been affected also by the Illinoian glacier.

Five main diversions were created by the Wisconsin ice. Diversions in the valleys of the unnamed southwest tributary of Rocky Fork, 3 miles northeast of St. Louisville, and of Lost Run, 3 miles east of St. Louisville, were both caused by the same thick deposit of end moraine and kames in southeastern Washington Township. The deep narrow valley of Claylick Creek, 3 miles southeast of Newark, was created when ice blocked a west-flowing stream in the valley at Fleatown. Quarry Run, just east of Jacksontown, was diverted from its original westward flow by the outermost Wisconsin end moraine. Three miles north of Granville, Dry Run, which once flowed to the southwest, up the valley of Griffin Run, now drains eastward through the bedrock hills into the Licking River.

### TERRACES

Gravel outwash terraces of both Wisconsin and Illinoian age are present in the county. Terraces along the valleys of the Licking River and its main tributaries were studied by Jones (1959), whose mapping, with minor modifications, appears on this map. Illinoian outwash, in the valleys of the Licking River, Brushy Fork in Perry Township, and Wilkins Run in Mary Ann Township, forms flat extensive plains of sand and gravel, whose eastern edges slope steeply down into the valleys. Illinoian outwash also forms the higher level on the north side of the Licking valley between Newark and Hanover. Because this outwash is not present on the south side of the valley, it is likely that it actually represents a kame terrace, formed while a tongue of ice occupied much of the Licking valley. This interpretation is supported by the somewhat irregular surface on this deposit and the presence, locally, of significant amounts of till.

Two levels of Wisconsin constructional terrace are recognized, a higher Vanatta Terrace and a lower Utica Terrace (Jones, 1959). In addition, lower, cut terraces are present in most places. Contrary to Jones' original mapping, the Vanatta Terace is now recognized along the Licking valley in the St. Louisville area and along Raccoon Creek three miles southeast of Johnstown, just west of Hazelton Corners. At this latter location, the terrace is locally capped by Centerburg Till. Around Granville, there are matched constructional terraces, not reported by Jones (1959), which stand approximately 20 feet above the level of the Vanatta Terrace and are here called the Granville Terrace. The existence of this terrace is best explained by the presence of resistant bedrock, since removed by erosion, in the valley of Raccoon Creek about a mile east of Granville. Terraces in areas so separated from the Licking drainage that dependable correlation was not possible are mapped as "undifferentiated Wisconsin terrace." These terraces commonly contain more silt and colluvium than gravel. Terrace levels cut into sandstone are locally present in the northeast corner of the county along Wakatomika Creek; these are indicated on the map by the symbol - Wtr.

LOCATION OF LICKING COUNTY, OHIO

BASE COMPILED FROM THE FOLLOWING U. S. GEOLOGICAL SURVEY TOPOGRAPHIC MAPS

EAST COLUMBUS
FRAZEYSBURG
FREDERICKTOWN
GAMBIER
GRANVILLE
MARENGO
NEWARK
THORNVILLE
THURSTON
WESTERVILLE
ZANESVILLE

# GLACIAL MAP OF LICKING COUNTY, OHIO

BY

JANE L. FORSYTH

REPORT OF INVESTIGATIONS NO. 59

STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
Ralph J. Bernhagen, Chief

### REFERENCES CITED

Dove, G. D., 1960, Water resources of Licking County, Ohio: Ohio Div. Water Bull. 36, 96 p.
Flint, N. K., 1951, Geology of Perry County: Ohio Geol. Survey Bull. 48, 234 p.
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