Appendix VII
RCRA Ground Water Flow Modeling Report for the Cedarville Aquifer

RCRA GROUND WATER FLOW MODELING REPORT FOR THE CEDARVILLE AQUIFER

VERNAY LABORATORIES, INC.
PLANT 2/3 FACILITY
Yellow Springs, Ohio

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TABLE OF CONTENTS

List of Figures

Table of Contents (cont.)

List of Tables

List of Attachments

1.0 OBJECTIVES

This report was prepared on the behalf of Vernay Laboratories, Inc. (Vernay), Yellow Springs, Ohio, and in conjunction with The Payne Firm, Inc. (Payne Firm), to provide information for Vernay's RCRA Corrective Action Phase I Facility Investigation (RFI) Report submittal. This report is an appendix to the Phase I RFI report. The objectives of this report are to:

- Describe the ground water flow field in the Cedarville Aquifer located beneath the Vernay Plant 2/3 Facility (Facility), and in the area surrounding the Facility. The Cedarville Aquifer is the uppermost aquifer beneath the Yellow Springs, Ohio area, and is contaminated with hazardous constituents at, or from the Facility.
- Determine the effectiveness that two existing capture wells, CW01-01 and CW01-02, located on the Facility have on controlling the migration of hazardous constituents in the Cedarville Aquifer.

These objectives were achieved using the following model simulations:

1. A three-dimensional ground water model that generates a flow field (array of head values) representing average conditions in the Vernay area.
2. A particle tracking analysis that evaluates how the average flow field, along with other transport parameters, is affected by the pumping at two capture wells located along the eastern property boundary of the Facility (CW01-01 and CW01-02).

The three-dimensional computer model for analyzing ground water flow presented in this report will assist in estimating the movement of hazardous constituents in ground water that have migrated beneath the property boundary of the Facility (i.e. chemical fate and transport model), and more importantly, in understanding the rate of contaminant degradation off of the Facility during different remediation scenarios. These analyses will be completed during Phase II of the RFI, and during the evaluation of corrective remedial measures for the Facility. The chemical fate and transport model cannot be completed until the ground water flow mode is developed and calibrated using site-specific data and information.

The modeling results presented in this report are based on an extensive review of the area's geologic history, the occurrence and movement of ground water beneath the Yellow Springs area, geologic, hydrogeologic, and ground water chemical data collected in the Yellow Springs area by the Ohio EPA, Payne Firm, Yellow Springs Instruments, Inc. (and its consultant, BHE Environmental, Inc.), Panterra, Inc. and Bennett and Williams, Inc. on the behalf of the Village of Yellow Springs, and others (the primary references used in preparing this report are cited in Section 8).

2.0 STEPS REQUIRED IN COMPUTER MODELING

Steps completed in creating the numerical model included the following:

1. Adopting a conceptual model to guide the development of the model.
2. Choosing appropriate computer code(s) for the analysis.
3. Establishing the time period represented by the model and the duration of subdivisions of this period (time steps) required for modeling.
4. Selecting a suitable model domain, including determining the dimensional (horizontal and vertical) limits of the analysis.
5. Establishing the model structure, including determining the number of model layers and the grid spacing requirements.
6. Incorporating hydraulic boundaries and features, including determining the shape and characteristics of constant-head boundaries, rivers, precipitation (or other) recharge sources, and pumping wells.
7. Assigning hydraulic parameters consisting of hydraulic conductivity, total porosity, effective porosity, storativity, and initial head (ground water surface elevation) values.
8. Selecting hydraulic calibration targets.
9. Evaluating and assigning appropriate model computational characteristics, for example, solution method, iteration limits and convergence criteria, to enhance model stability, computational efficiency, and solution accuracy.
10. Running the model and adjusting assigned model parameters within predetermined limits to achieve the closest fit between model results and calibration targets.

Completion of these steps is necessary to create a model representing field conditions as accurately as possible within the constraints of practicality and data availability.

2.1 Basic Aspects of Computer (Numerical Modeling)

A fundamental condition prevents easy and accurate analyses of ground water flow conditions and the movement of chemicals in ground water. There are many parameters that must be considered that the use of an analytical (mathematical) solution for ground water flow (or contaminant transport) is not possible. Typical variables include hydraulic conductivity, porosity, dispersivity, and rates of chemical volatility, transformation, biodegradation, and sorption. Each of these parameters can change independently of the other variables as a contaminant plume originating at the chemical source area flows downgradient. Thus, a rigorous analysis of ground water flow and contaminant transport requires a solution method that can accommodate a large number of variables whose values may change significantly from one part of the plume to another. Numerical (mathematical) modeling has been developed to solve this type of complex problem.

Prior to conducting numerical modeling, however, the researcher must have an adequate understanding of the processes that control ground water flow and contaminant transport. This understanding or conceptualization is often termed a conceptual model. The components of the conceptual model for the Vernay Facility are presented in Section 3 of the Phase I RFI report and describe the present conditions. Ideally the modeler should be a good 'field hydrogeologist' who is familiar with the nature of the geologic terrane to be modeled. The hydrogeologist develops a conceptual model of the hydrogeologic environment based on field experience. This conceptual model provides a vital guide in creating a numerical model that represents actual field conditions. Although the goal of any modeling endeavor is to represent the characteristics of the ground water system and any chemical sources as simply as possible, the results of the computer analysis will inevitably be in error if the conceptual model is flawed.

To make predictions of future behavior, however, it is necessary to derive a mathematical model from the conceptual model. A mathematical model is essentially a mathematical representation of a process or system conceptual model that describes the physical conditions that control the ground water movement at the site. These conditions can be described by solving certain governing equations that describe ground water flow. When these governing equations are applied in three dimensions, however, they become difficult to solve analytically (by direct computation) even for simple ground water systems. They are impossible to solve when the characteristics of the ground water system vary from place to place, when hydraulic or chemical conditions change with time, or when the system includes multiple hydraulic or chemical features (for example, lakes, rivers, pumping wells or multiple chemical sources). Thus, the most popular models use a numerical (mathematical) technique, called the 'finite-difference method,' that substitutes a set of simpler finite-difference equations for the complex flow and transport equations. Models that use this technique, therefore, are called numerical models.

Constructing a model that uses the finite-difference technique requires that the ground water system be divided ('discretized') into finite-sized blocks or 'cells.' Each cell can be assigned unique hydraulic and transport properties depending on the available field data and the goals for the analysis. In this way, complex features of the ground water system can be accommodated in the model. The time represented by the modeling effort must also be divided into discrete periods or 'time steps.' These steps must be short enough to provide an accurate solution, but not so short that they require an excessive number of calculations to run a simulation. The finite-difference method also requires that values for head be assigned at flow boundaries (referred to as 'boundary conditions'), as well as for the initial time period of the simulation (referred to as 'initial conditions'). This is a requirement for producing a unique solution with any numerical method that depends on iteration, as does the finite-difference method.

After assigning properties and initial and boundary conditions, the finite-difference equations for flow are solved to produce a mathematically 'approximate' but scientifically reliable value of the average ground water head (potentiometric surface elevation) within each cell. Models that use the finite-difference numerical technique allow rapid analysis of complex, time-dependent ground water systems, making them popular for all but the simplest scenarios.

Following the formulation of the numerical model, the computer program (or code) is developed. This consists of the assembly of numerical solution techniques, bookkeeping requirements, and computer language (e.g., FORTRAN) that represents the mathematical model derived from the conceptual model which uses input parameters representative of the hydrogeologic system and the computer language instructions to calculate results that are used to predict the behavior of the system. The code is a generalized set of steps, to which specific field conditions, such as initial and boundary conditions, are imposed. Various model codes are available; some are proprietary (privately owned), while others are in the public domain (available to everyone). The most widely used codes for describing ground water flow is MODFLOW, which was developed by the United States Geological Survey and is in the public domain.

The conceptual, mathematical and numerical models are based on the modeler's experience and represent the modeler's understanding of the physical system being modeled. The conceptual model, and consequently the mathematical and numerical models, will become more complex as more processes are identified and interrelationships of important components within the systems are considered. The transformation of the conceptual model into a mathematical model is only an extrapolation of a basic understanding of the system and will result in simplifications of the system. For example, the mathematical models assume that there is a direct scaling between the model simulations and the scale at which the data are collected. The lack of knowledge about the system resulting from limited information also contributes to simplifications of the models. In addition to these unavoidable simplifications, there are simplifications in which the modeler decides what physical characteristics and processes are important to the model application. All of these considerations constitute the theoretical basis upon which the models are formulated, and lead to constraints and limitations under which they may be applied.

3.0 CONCEPTUAL MODEL

A conceptual model was developed to serve as the basis for the construction of the computer (numerical) model. A conceptual model generally summarizes the theoretical understanding of the primary conditions that affect ground water flow and chemical transport and fate. Although the most significant elements of this conceptual model are outlined in Section 3 of the Phase I RFI report, site specific conditions particularly relevant to the construction of the computer model are presented below:

- The Facility is located near a regional surficial and bedrock topographic high area. The unconsolidated deposits in the vicinity of the Facility consist of glacial clay till deposits. Two carbonate bedrock aquifers are present beneath the Facility and surrounding area. The uppermost aquifer, defined as the Cedarville Aquifer, is approximately 74 to 89 feet thick beneath the Facility and vicinity. A lower aquifer, the Brassfield Aquifer, is approximately five feet thick. Up to approximately 70 to 100 feet of shale and carbonate rock (the Osgood Aquitard and Brassfield Aquitard) separates the two bedrock aquifers. A very low permeability interbedded limestone and shale deposit (Elkhorn Aquiclude) represents the bottom of the hydrogeological system beneath the Facility.

- Based on local ground water elevations measured on September 10, 1999 before ground water capture began at CW01-01, ground water flow beneath the Facility and the surrounding area is towards the east-northeast at an estimated gradient of 0.005 ft/ft, and the calibrated hydraulic conductivity of the Cedarville Aquifer ranges from 60 to 5,500 feet per year. Therefore, the ground water flow velocity in the Cedarville Aquifer ranges from approximately 5 to 75 feet per year (if an effective porosity of 25 percent is assumed).
- Ground water flow within the Cedarville Aquifer is primarily horizontal. Water level measurements from wells that are screened within upper, middle and lower intervals of the Cedarville Aquifer indicate almost no vertical hydraulic gradient (see Section 3.0 of the Phase I RFI Report). In most instances, less than 0.2 feet of head is measured between the three Cedarville Aquifer intervals and a slight upward hydraulic gradient is observed from the lower to upper interval. As a result, downward vertical ground water movement is limited within the aquifer, and restricted by the laterally extensive Osgood and Brassfield aquitards that occur at the base of the Cedarville Aquifer beneath the Facility, and the surrounding area.
- The Cedarville Aquifer can be represented as an equivalent porous medium at the scale of the Facility and vicinity. This is supported by the following: 1) the results of the aquifer pumping test performed on CW01-01 shows little evidence of anisotropy or delayed yield characteristics typical of discrete fracture systems; 2) there is very little vertical hydraulic head present in wells screened in the upper, middle and lower portions of the aquifer; 3) the potentiometric surfaces of the Cedarville Aquifer exhibit a smooth and continuous surface without areas of rapidly changing or anomalous hydraulic head values; 4) the measurement of natural ground water geochemical parameters such as temperature, pH, and specific conductivity are relatively constant on a quarterly basis; and 5) site specific geophysical and rock core inspection indicates that ground water flow is predominantly controlled by horizontal bedding plane partings.

4.0 COMPUTER CODE SELECTION

The computer codes that were used for this analysis are MODFLOW and MODPATH. MODFLOW, the United States Geological Survey (USGS) finite-difference ground water flow model, is a popular, publicly available and widely accepted computer code. Ground water flow within the aquifer is simulated using a block-centered finite-difference approach. Layers can be simulated as confined, unconfined, or a combination of confined and unconfined. Flow associated with external stresses, such as wells, areal recharge, evapotranspiration, drains, and streams can also be simulated. Computer files used in the MODFLOW and MODPATH software are included in Attachment I of this report.

MODPATH is a particle tracking post-processing package that was developed to compute three-dimensional flow paths using output from steady-state or transient ground water flow simulations by MODFLOW. MODPATH is described in USGS Open-File Reports 89-381 and 89-622. MODPATH uses a semi-analytical particle tracking scheme that allows an analytical expression of the particle's flow path to be obtained within each finite-difference grid cell. Particle paths are computed by tracking particles from one cell to the next until the particle reaches a boundary, an internal sink/source, or satisfies some other termination criterion.

5.0 MODEL CONSTRUCTION

One primary goal of mathematical modeling is to synthesize the conceptual model into numerical terms from which flow and transport processes may be investigated under specified conditions. This process entails several discrete steps: (1) partitioning the conceptual model into units of time and space, (2) specification of the values of parameters, and (3) assignment of boundary conditions. The following sections briefly discuss the approach taken and the relevance of each of these topics to the modeling process.

5.1 Finite Difference Grid Development

The determination as to what area should be included in the model is typically based on the presence of natural hydrogeologic boundaries. Ideally, the modeled area would be completely surrounded by streams, ground water divides and/or rocks of very low permeability. These types of features greatly assist in defining the boundaries of the system. The boundaries used for the model are discussed below in Section 4.3.

In a numerical model, the region of interest is partitioned into a series of grid blocks (i.e., elements), which are arranged in layers. This practice, termed discretization, effectively replaces the continuous problem domain with an array of blocks. The basic concept involves dividing up the area as realistically as practical. When possible, geologic logs and other information typically are used to identify geologic unit contacts. One of the critical steps in applying a ground water model is selecting the size of the grid blocks. Smaller grid blocks lead to more accurate numerical solutions. The desire for accuracy, however, must be balanced against the impracticality of solving for large numbers of nodes and the long computer run times that may be involved. For this modeling exercise, a finite difference grid (i.e., squares and rectangles) was adopted with 27,702 active cells that range in length from 0.35 ft, in the vicinity of particularly relevant features (e.g., pumping and monitoring wells), to 55 feet at the model boundaries.

5.2 Stratigraphy and Model Parameterization

The determination of how many model layers to include depends on both the conceptual model and the objectives of modeling. Typically, multiple layers are used to accommodate the vertical variation of hydrologic parameters that represent the hydrogeologic units within the modeled region. In the modeled area, however, there is very little evidence that vertical variations in the lithology are controlling ground water flow. Therefore, a single model layer that is approximately 75 feet thick is used to simulate ground water flow through the upper, middle and lower portions of the Cedarville Aquifer. This conceptualization may need to be changed, however, if contaminant transport simulations are conducted at some point in the future.

5.3 Boundary and Initial Conditions

To obtain a solution for the governing equation of ground water flow, information is required about the physical state of the ground water system. This information is described by boundary and initial conditions. Boundary conditions are the conditions the modeler specifies as known values to solve for the unknowns in the problem. These values may be associated with either ground water flow or contaminant transport. Boundaries generally are quantified in terms of the volume of ground water and contamination moving through the system. The physical boundaries are then translated into mathematical terms and input into the computer model. For example, if the surface of the stream is known to be five feet above mean sea level, this knowledge can easily be translated into the model as a constant-head boundary; that is, a constant head which is set to five feet. Areas in which very little ground water flow passes would be set to no-flow model boundaries.

In designing the mathematical model, the boundaries of the model should be prescribed at sufficient distances to ensure that the modeling results are not significantly prejudiced by 'boundary effects'. These effects are associated with the strong mathematical influence that a boundary condition will have over the immediate area. For example, a constant head boundary condition is one in which a cell (or series of cells) will be assigned a ground water elevation value that will remain constant throughout the simulation. The water level elevations in model cells that are in the immediate vicinity of the boundary will tend to be very insensitive to other model input parameters (e.g., hydraulic conductivity, recharge). This relative insensitivity to varying model input makes the model predictions very unreliable in the immediate vicinity of the model boundaries. This requirement of placing the model boundaries away from the region of primary interest often becomes problematic, however, because there is frequently very little available data on which to base the model boundaries.

During the week of February 14, 2000, local and regional water levels were collected over a six square mile area extending from approximately one mile to the north, east and west of the Facility and two miles south of the Facility. Contours of these regional water levels were used to assign constant heads on the lateral hydraulic boundaries of the more localized model (Figure 1). The base of the model was assigned a no-flow boundary since the Cedarville Aquifer is underlain by the Osgood and Brassfield aquitards. The uppermost boundary is defined by areal recharge and is assigned a constant flux of 7 inches per year. The two capture wells on the Facility (CW01-01 and CW01-02) affect ground water flow in the modeled area. The wells withdraw ground water from the model at a rate of seven gallons per minute.

Initial conditions are simply the values of hydraulic head or contaminant concentrations at a reference initial time. For steady-state problems, only boundary conditions are required; whereas, for transient problems, both conditions are required. Since the model was calibrated under steady-state conditions, as described below, initial conditions were not required.

6.0 MODEL CALIBRATION

The purpose of a mathematical model is to produce numbers. These numbers are the model's predictions of what a natural or man-made system will do under a certain regime. It is for the sake of these numbers that the model was built, be it a ten-line program involving a few additions and subtractions, or a complex numerical procedure for the solution of coupled sets of nonlinear partial differential equations. Where a model simulates reality, it often happens that the model-user does not know what reality is. In fact, models are often used to infer reality by comparing the numbers that they produce with numbers obtained from some kind of measurement. Thus, if a model's parameter data are "tweaked", or adjusted, until the model produces numbers that compare well with those yielded by measurement, it can be reasonably be assumed that the parameters so obtained have actually told us something which we could not obtain by direct observation. Thus if a ground water model is able to reproduce the variations in monitoring well water levels over time (a quantity which can be obtained by direct observation), the hydraulic conductivity values that are assigned to different parts of the model domain in order to achieve this match may be correct. This is fortunate as it is often difficult or expensive to measure rock hydraulic conductivities directly.

Traditionally, the term "model calibration" is used to refer to the trial-and-error adjustment of parameters of the ground water system by comparing the model's output (calculated values of hydraulic head or concentration) and the measured output (observed values of hydraulic head or concentration). In essence, such a calibration procedure involves the following routines: (1) operating the model, using initial estimates of the values of parameters, (2) history-matching, or comparing computed and observed values of hydraulic head or concentration, and (3) adjusting the values of the parameters and repeating the simulation.

Calibration of the model is aimed at demonstrating that it can produce realistic, accurate and reliable predictions. The flow model is calibrated by determining a set of parameters, boundary conditions, and hydraulic stresses that generate simulated potentiometric surfaces and fluxes that match field-measured values to within an acceptable range of errors. The end result of the process of model calibration is an optimal set of values for parameters that minimize the discrepancy between the model's output and the observed data. The iterative process of matching calculated values with observed (historical) data by adjusting the model's input can be a manual trial-and-error procedure or can be automated. The calibration process, also known as history-matching, is closely related to estimating parameters. This process might result in the refinement of initial estimates of aquifer properties (parameters), the establishment of the location of the boundaries (areal and vertical extent of aquifer), and the determination of flow and transport conditions at the boundaries.

Calibration can be performed to steady-state or transient data sets. Although most flow model calibration exercises involve steady-state data, in some hydrogeologic settings, assumption of steady-state conditions may be inappropriate due to large fluctuations in the water table or boundary conditions. In this case, the model may be calibrated against long- or short-term trends in water levels, stream and lake elevations and, possibly, system responses resulting from imposed stresses such as pumping wells.

In order to facilitate the model calibration a parameter estimation tool was implemented. Parameter Estimation (PEST) is a calibration tool, developed by Watermark Computing, that uses non-linear least-squares techniques to adjust model parameter data in order that the discrepancies between the pertinent model-generated numbers and the corresponding measurements are reduced to a minimum. It does this by taking control of the model and running it as many times as is necessary in order to determine this optimal set of parameters. Computer files used in the PEST software are included in Attachment I of this report.

Initial calibration of the steady state flow model was accomplished iteratively during successive model runs by matching ground water elevations in the Cedarville Aquifer to ground water levels measured in March 2004. The March 2004 water level data constitute the most extensive set of contemporaneous hydraulic data available and currently provide the most reliable basis for flow calibration. Data from 52 observation points were ultimately used for calibration. Statistical analyses of the modeled ground water elevations indicate that all values are well within the range expected for a well-calibrated model. The residual standard deviation of the estimate is 0.28 ft. The primary measure of calibration accuracy used by many modelers (the normalized root mean squared error of the estimate) is less than two percent for the flow model. This low value indicates that the differences between model-calculated and field-measured heads are only a small part of the actual head changes in the modeled area. The equipotential surfaces produced by the model are shown on Figures 2A-2D.

The residual error for each of the monitoring wells, which is determined by comparing the measured water-level values to those predicted by the model are shown in Table 1. This information is also presented in Figures 3 and 4. As shown in Figure 3, the entire model predicted values fall within ± 0.78 feet of the field measured values. Most of the model predictions, however, are within ± 0.25 feet of their actual values. In Figure 4, the error residuals (difference between the model predicted and actual values) have been posted adjacent to their respective monitoring and pumping wells. As shown in this figure, the greatest errors tend to be located in the immediate vicinity of the two capture wells. Although the errors in this area are still relatively small they indicate that the model is not predicting the shape of the drawdown curve exactly. With respect to defining the extent of the capture zone, however, the shape of the drawdown curve in the immediate vicinity of the pumping wells will have essentially no impact on delineating the overall capture area. It is far more important to obtain a good calibration to the well data located along the fringe of the capture zone, as this information will define the area that is actually captured.

The model results have been plotted against measured values in Figure 5. In a perfectly calibrated model the data would fall on a straight line. The results of this plot indicate that the model predictions provide an acceptable match to the data over the entire range of simulated hydraulic heads.

As shown in Figure 6, the calibrated hydraulic conductivities of the Cedarville Aquifer tend to fall between 60-5,500 ft\yr. The higher hydraulic conductivities (shown in warmer colors) are generally between 1,000 and 5,500 ft/yr, and form a band that trends from the southwest to the northeast. This zone of higher hydraulic conductivity is not only consistent with the northeast trending hydraulic gradients, but it is also aligned with the general shape of the contaminant plumes which are presented in Section 5 of the Phase I RFI report. It is believed that joints in the Cedarville Aquifer units are the cause of this zone of increased hydraulic conductivity in the vicinity of the Facility and is consistent with the joint trends mapped by others in the region.

7.0 PARTICLE TRACKING ANALYSIS

Once the flow model was calibrated, the computer code MODPATH was used to define flow directions (i.e., capture zones) based on the calibrated hydraulic heads and conductivities. MODPATH is a widely accepted three-dimensional particle-tracking model that works with MODFLOW (and was developed by the USGS). Particle tracking is a form of transport modeling that represents the bulk movement of ground water. Particle tracking neglects the effects of chemical reactions, dispersion, and diffusion. The particle tracking analysis involves adding particles to the model at selected locations and then allowing the model to move the particles in the direction of ground water flow. The results of a particle tracking simulation are displayed by plotting pathlines through the aquifer system. As shown in Figure 7, all of the particles placed within the model are captured by the two existing extraction wells (i.e., CW01-01, CW01-02) located along the eastern property boundary of the Facility. Computer files used in the MODPATH software are included in Attachment I of this report.

8.0 SUMMARY AND CONCLUSIONS

The hydrologic conceptual site model is being developed to collect and process information on the subsurface water flow and lithology in order to analyze the Vernay area as a system and investigating water flow in terms of mass balance and ground water budgets throughout the investigational area. A properly calibrated numerical model that simulates ground water flow provides investigators a means to predict the system behavior to natural and manmade stresses placed upon the system. Hydrologic analysis is being conducted using MODFLOW, PEST and MODPATH software programs. The use of PEST has allowed the model to be calibrated well beyond what was once considered practicable, and subsequent results of capture zone analysis indicate that the two extraction wells are effectively capturing the contaminated water emanating from the Vernay site.

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US EPA, 1994c; US EPA Contract Laboratory National Functional Guidelines for Organic Data Review; EPA-540/R-94-012.

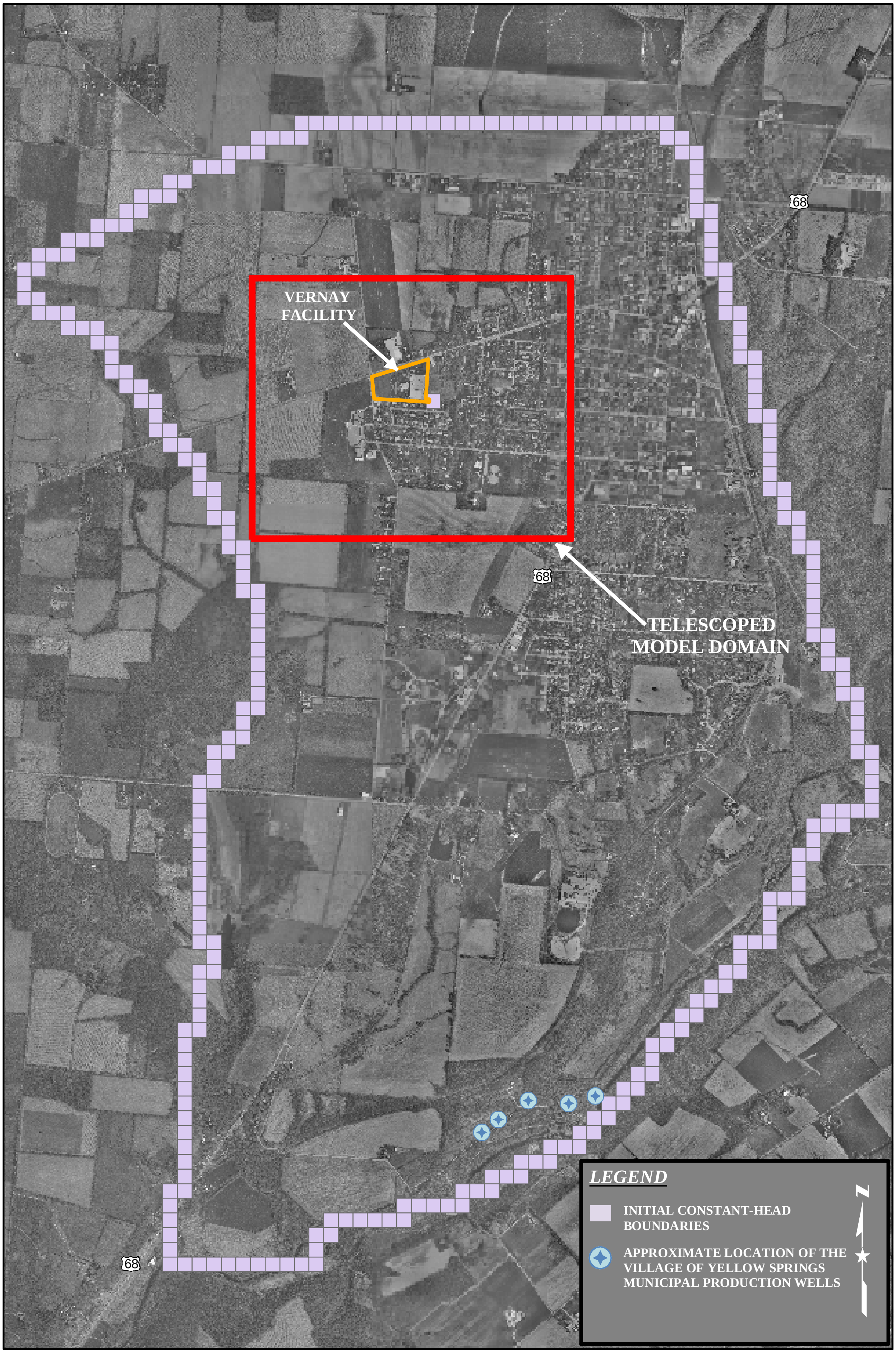
US EPA, 1994d; US EPA Contract Laboratory National Functional Guidelines for Inorganic Data Review; EPA-540/R-94-013.

US EPA, 2002; Handbook of Ground Water Protection and Cleanup Policies for RCRA Corrective Action; Office of Solid and Emergency Response; EPA/530/R-01/015.

Village of Yellow Springs, 2002; Comprehensive Plan.

Waren, K.B., 1988; Fracture Controlled Erosional Processes and Ground Water Flow in the Niagara Group Carbonates of Southwestern Ohio; Masters Thesis, Wright State University.

FIGURES



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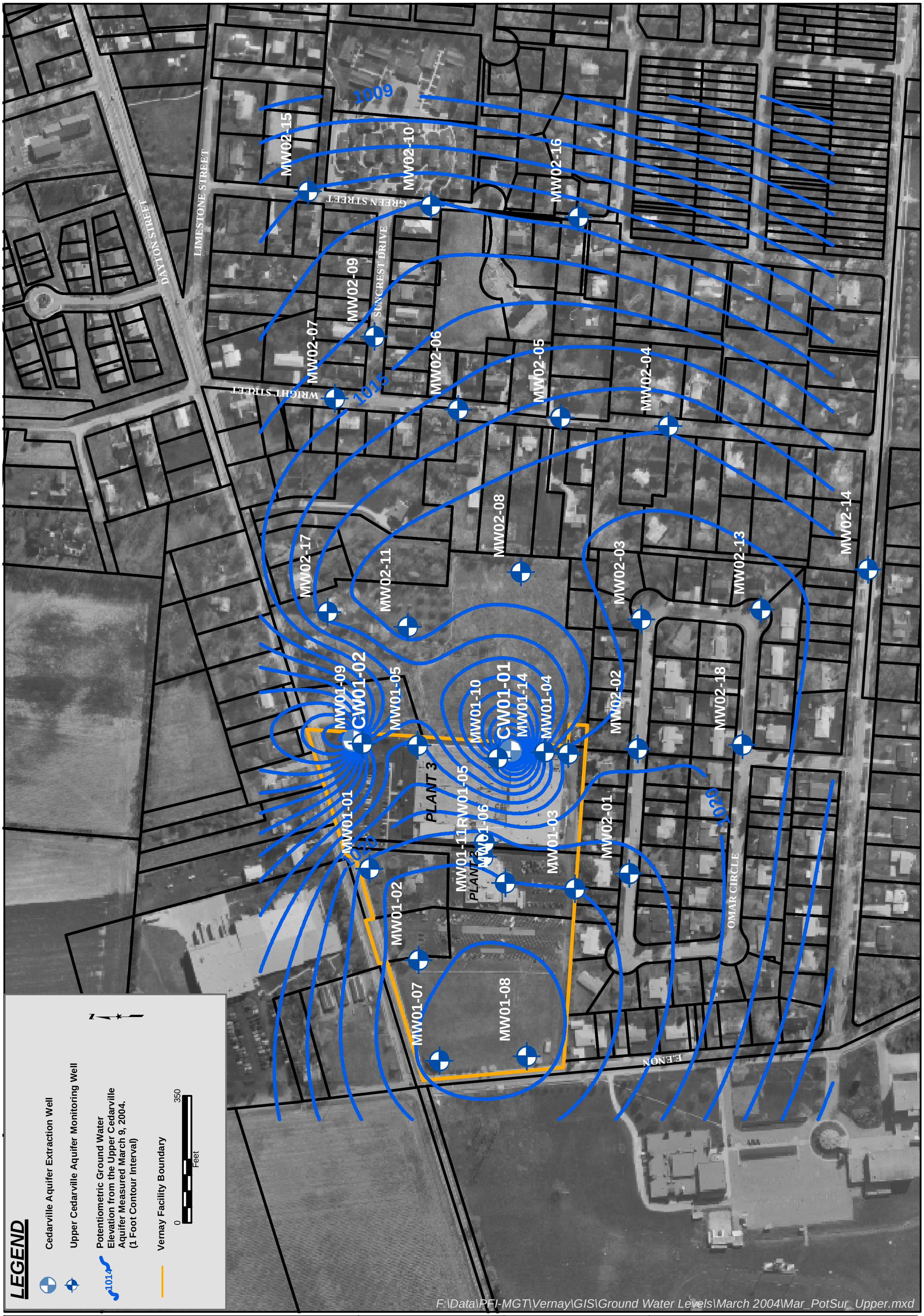
CLIENT: VERNAY LABORATORIES, INC.	FIGURE: 1	DATE: 12/17/03	The Payne Firm, Inc. Environmental Consultants Cincinnati, Ohio
TITLE: EXTENT OF HYDROGEOLOGICAL MODEL DOMAIN	DRAWN BY: ALH	APPROVED BY: KDK	
	PROJECT NO.: 0292.11.17		
REFERENCE: Green Co. Auditors, Orthophotograph (1998); Village of Yellow Springs 2001 Wellhead Protection Management Plan; Ground Water Resources of Green Co., Ohio DNR Division of Water			

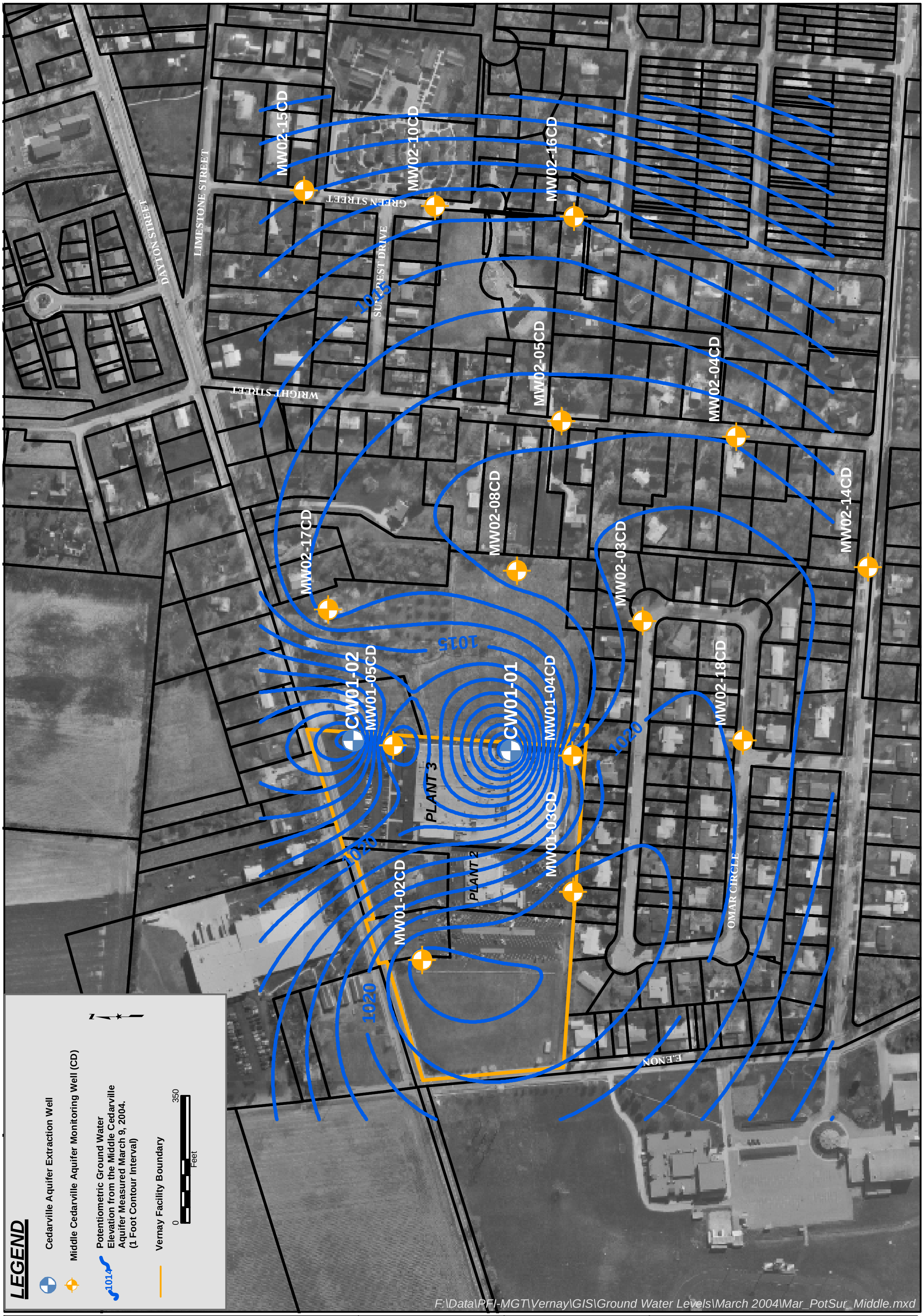
CLIENT: VERNAY LABORATORIES, INC.	FIGURE NO.: 2A	DATE: 5/19/04	The Payne Firm, Inc.
TITLE: MODELED EQUIPOTENTIAL SURFACES OF THE CEDARVILLE AQUIFER (MARCH 2004)	DRAWN BY: ALH	APPROVED BY: KDK	Environmental Consultants, Cincinnati, Ohio
	PROJECT NO.: 292.11.31		

REFERENCE *Greene County Auditors, Orthophotograph (1998); State Plane Coordinates from Woolpert Surveying, LLP, Dayton, Ohio (NAD83/NAVD88)*



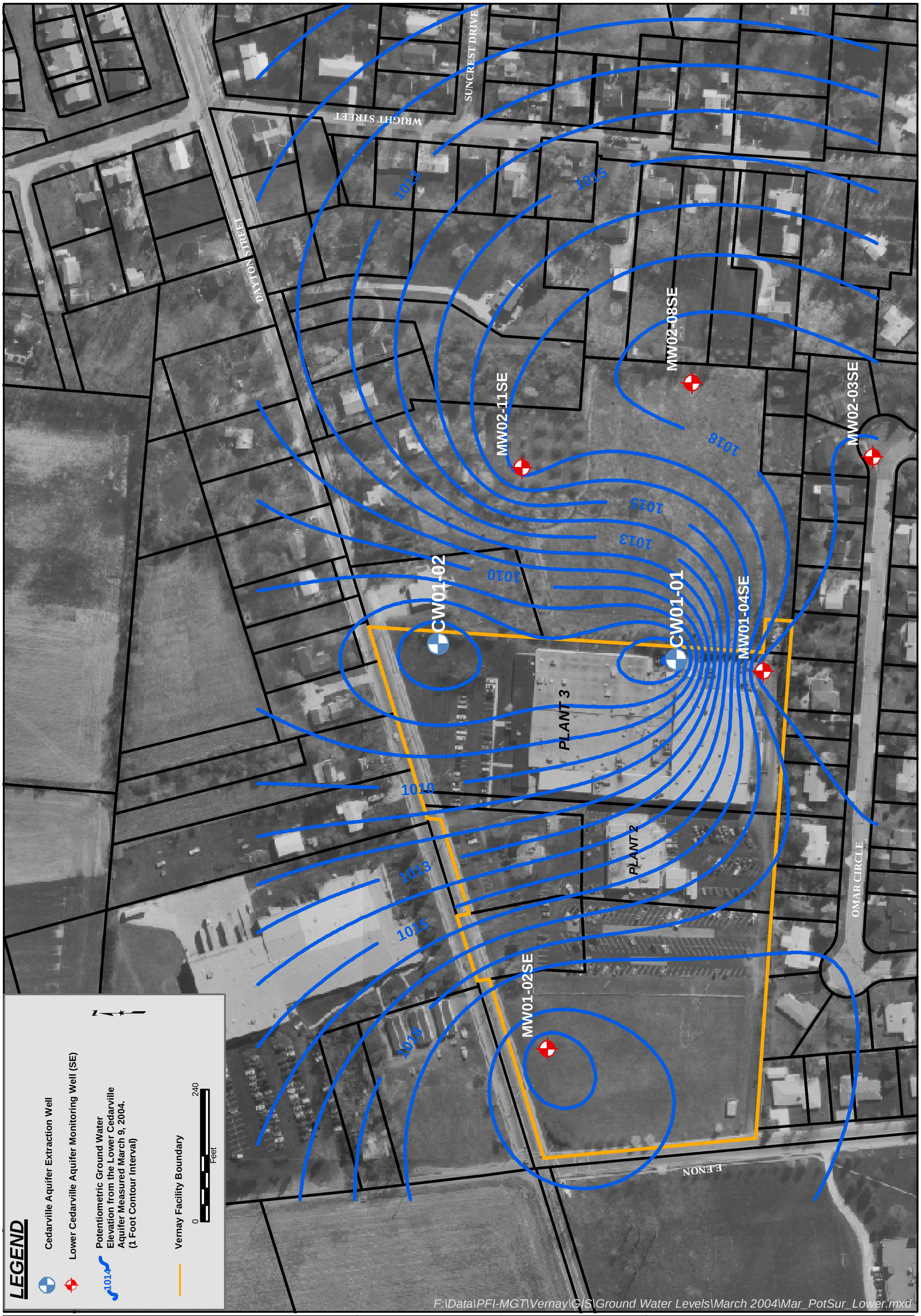
CLIENT VERNAY LABORATORIES, INC.	FIGURE NO. 2B	DATE 5/19/04	The Payne Firm, Inc. Environmental Consultants Cincinnati, Ohio
TITLE MODELED EQUIPOTENTIAL SURFACES OF THE UPPER CEDARVILLE AQUIFER (MARCH 2004)	DRAWN BY ALH	APPROVED BY KDK	
	PROJECT NO. 292.11.31		

REFERENCE Greene County Auditors, Orthophotograph (1998); State Plane Coordinates from Woolpert Surveying, LLP, Dayton, Ohio (NAD83/NAVD88)



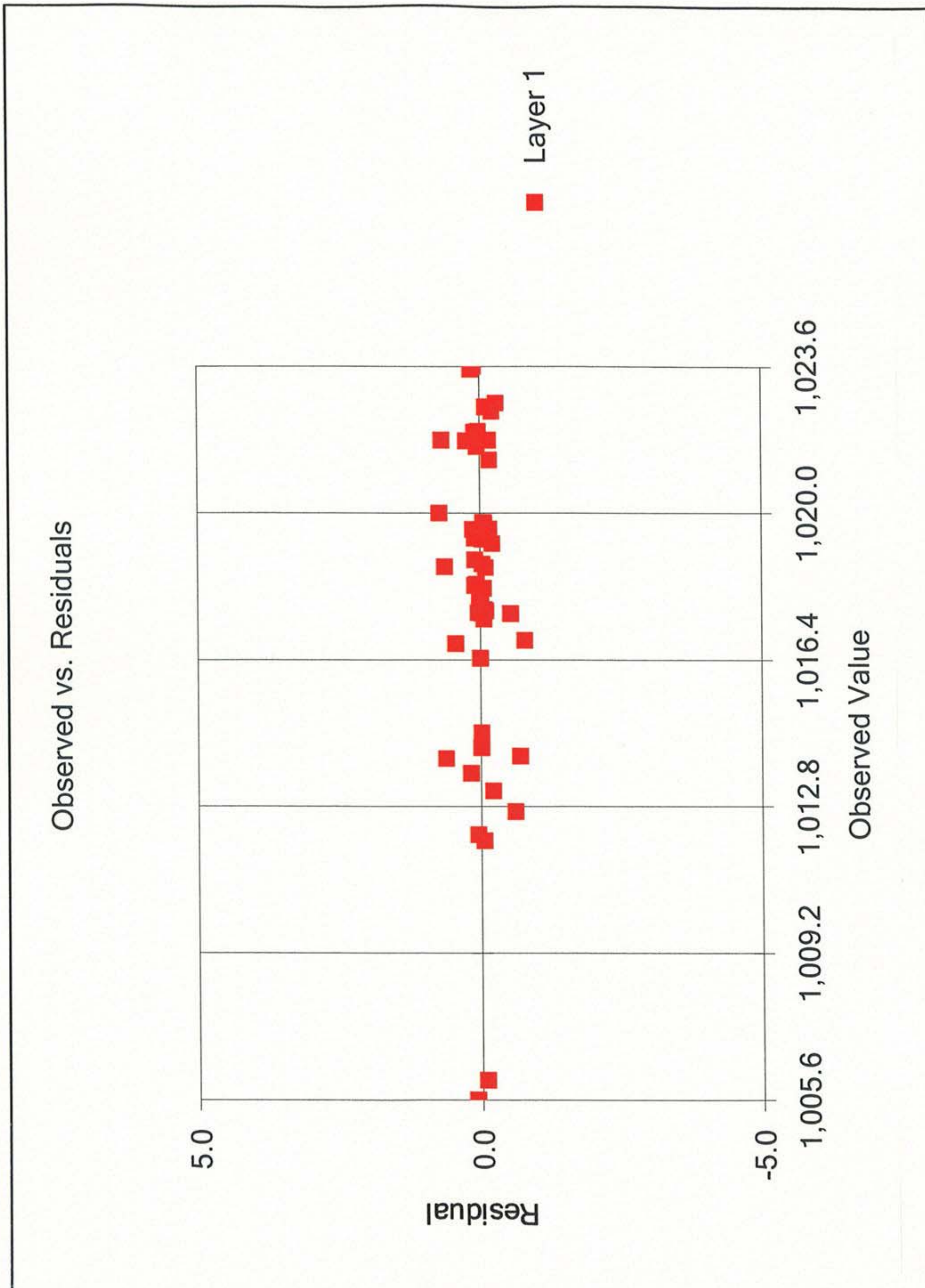
CLIENT VERNAY LABORATORIES, INC.	FIGURE NO. 2C	DATE 5/19/04	The Payne Firm, Inc. Environmental Consultants Cincinnati, Ohio
TITLE MODELED EQUIPOTENTIAL SURFACES OF THE MIDDLE CEDARVILLE AQUIFER (MARCH 2004)	DRAWN BY ALH	APPROVED BY KDK	
	PROJECT NO. 292.11.31		

REFERENCE *Greene County Auditors, Orthophotograph (1998); State Plane Coordinates from Woolpert Surveying, LLP, Dayton, Ohio (NAD83/NAVD88)*



CLIENT: VERNAY LABORATORIES, INC.	FIGURE NO.: 2D	DATE: 5/19/04	The Payne Firm, Inc. Environmental Consultants Cincinnati, Ohio
TITLE: MODELED EQUIPOTENTIAL SURFACES OF THE LOWER CEDARVILLE AQUIFER (MARCH 2004)	DRAWN BY: ALH	APPROVED BY: KDK	
	PROJECT NO.: 292.11.31		

REFERENCE: Greene County Auditors, Orthophotograph (1998); State Plane Coordinates from Woolpert Surveying, LLP, Dayton, Ohio (NAD83/NAVD88)



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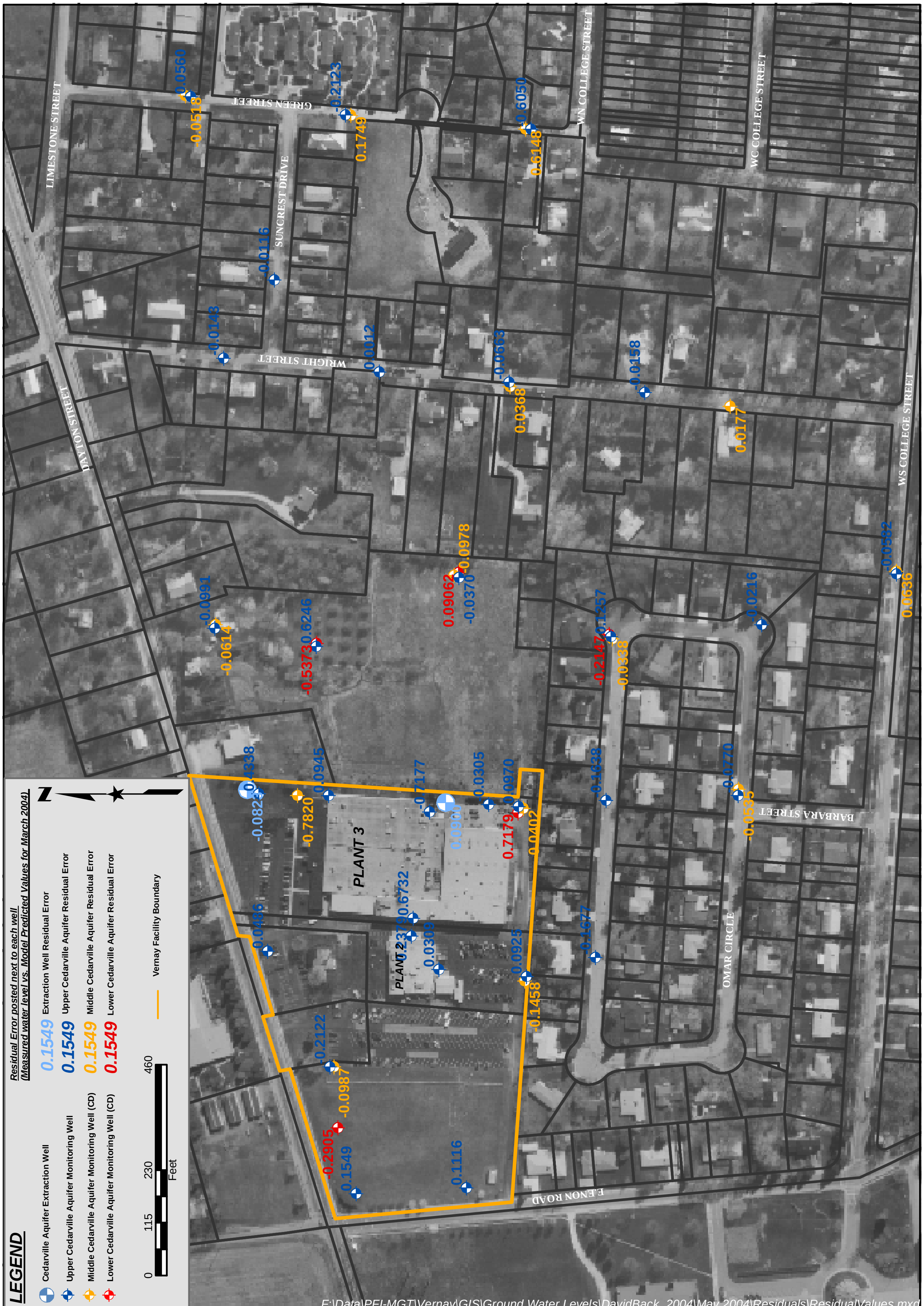
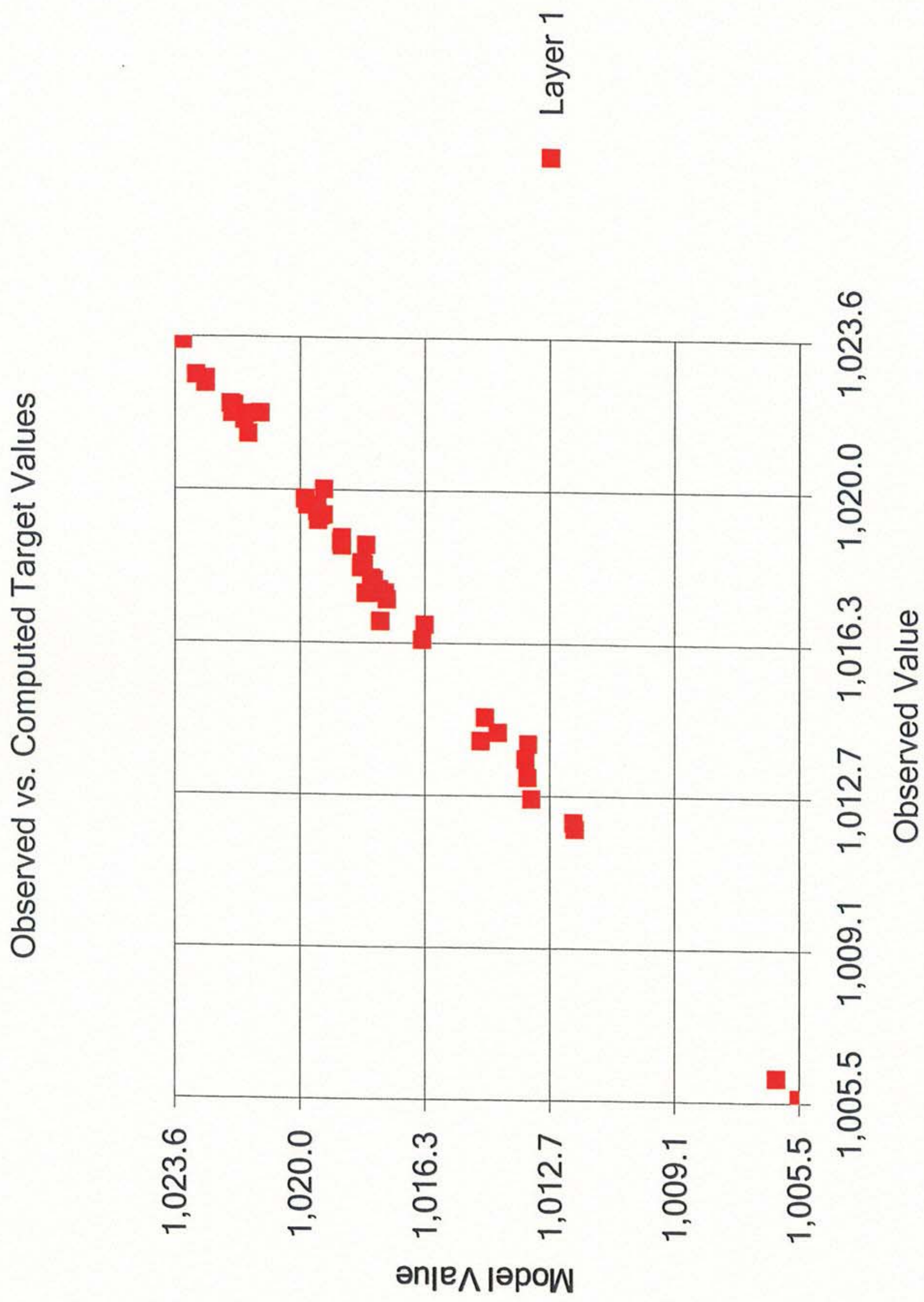
VERNAY LABORATORIES, INC.	FIGURE NO. 3	DATE 5/19/04	The Payne Firm, Inc. Environmental Consultants Cincinnati, Ohio
TITLE DISTRIBUTION OF RESIDUAL ERRORS FOR ALL CALIBRATION TARGETS (MARCH 2004)	DRAWN BY ALH	APPROVED BY KDK	
	PROJECT NO. 292.11.31		

REFERENCE Greene County Auditors, Orthophotograph (1998); State Plane Coordinates from Woolpert Surveying, LLP, Dayton, Ohio (NAD83/NAVD88)



CLIENT VERNAY LABORATORIES, INC.	FIGURE NO. 4	DATE 5/19/04	The Payne Firm, Inc.
TITLE RESIDUAL ERRORS FOR EACH MONITORING AND EXTRACTION WELL (MARCH 2004)	DRAWN BY ALH	APPROVED BY KDK	Environmental Consultants Cincinnati, Ohio
	PROJECT NO. 292.11.31		

REFERENCE Greene County Auditors, Orthophotograph (1998); State Plane Coordinates from Woolpert Surveying, LLP, Dayton, Ohio (NAD83/NAVD88)



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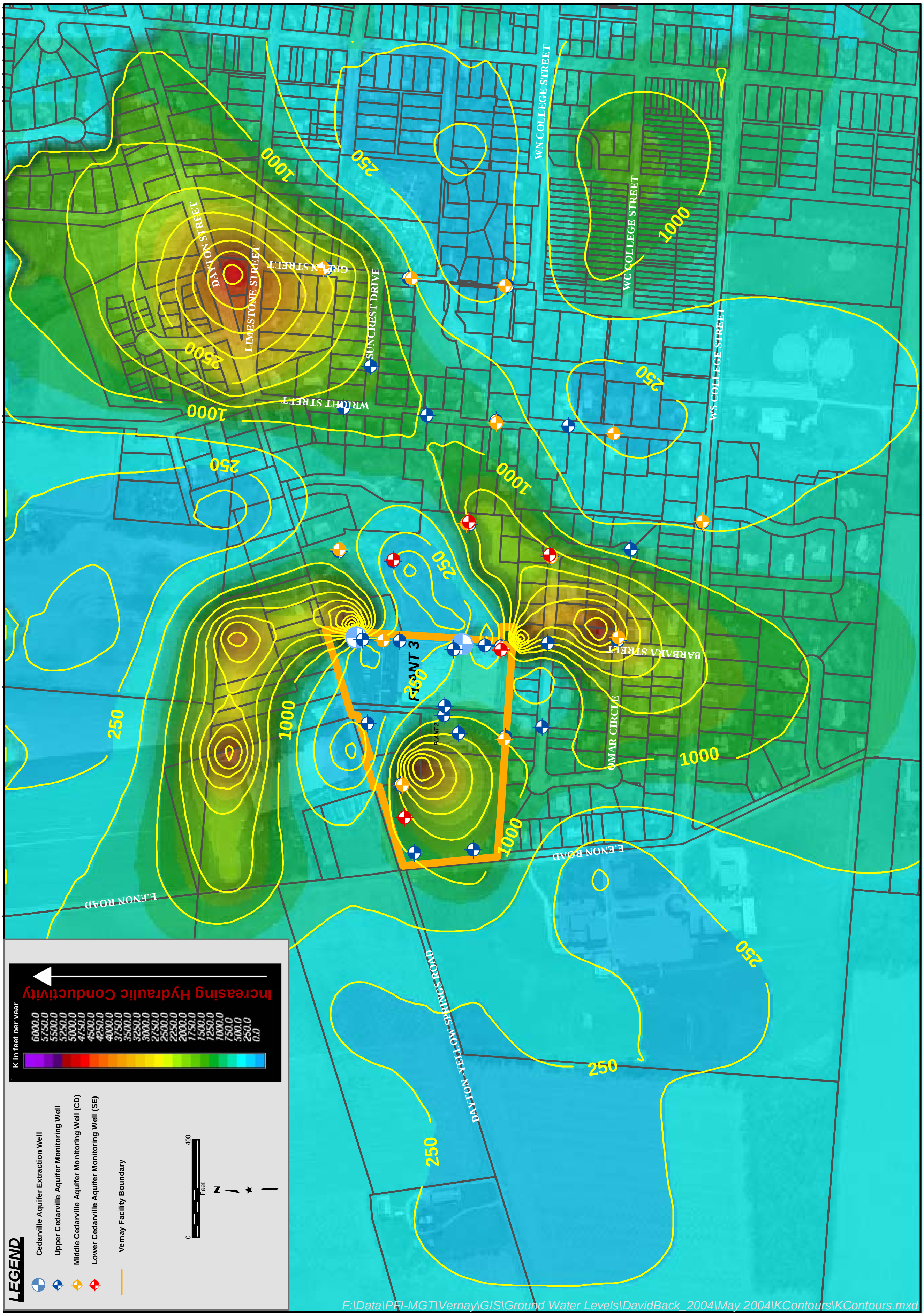
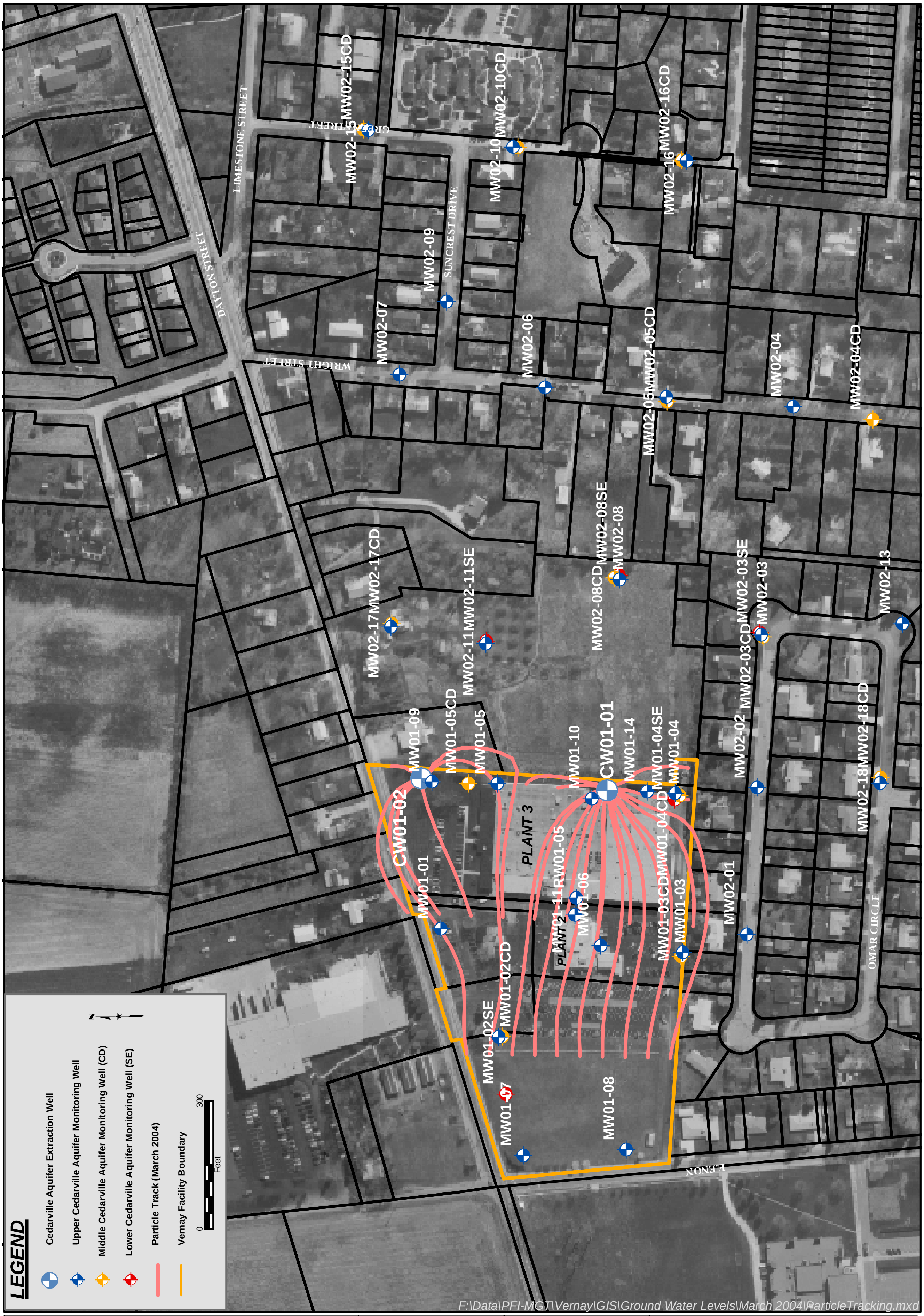
VERNAY LABORATORIES, INC.	FIGURE NO. 5	DATE 5/19/04	The Payne Firm, Inc.
TITLE *LINEAR RELATIONSHIP OF MODELED TO PREDICTED HEADS (MARCH 2004)*	DRAWN BY ALH	APPROVED BY KDK	Environmental Consultants Cincinnati, Ohio
	PROJECT NO. 292.11.31		

REFERENCE *Greene County Auditors, Orthophotograph (1998); State Plane Coordinates from Woolpert Surveying, LLP, Dayton, Ohio (NAD83/NAVD88)*



CLIENT VERNAY LABORATORIES, INC.	FIGURE NO. 6	DATE 5/19/04	The Payne Firm, Inc. Environmental Consultants Cincinnati, Ohio
TITLE CALIBRATED HYDRAULIC CONDUCTIVITIES OF THE CEDARVILLE AQUIFER (MARCH 2004)	DRAWN BY ALH	APPROVED BY KDK	
	PROJECT NO. 292.11.31		

REFERENCE Greene County Auditors, Orthophotograph (1998); State Plane Coordinates from Woolpert Surveying, LLP, Dayton, Ohio (NAD83/NAVD88)



CLIENT: *VERNAY LABORATORIES, INC.*	FIGURE NO.: 7	DATE: 5/19/04	**The Payne Firm, Inc.** Environmental Consultants Cincinnati, Ohio	
TITLE: *RESULTS OF THE PARTICLE TRACKING SIMULATION THROUGH THE CEDARVILLE AQUIFER (MARCH 2004)*	DRAWN BY: ALH	APPROVED BY: KDK		
	PROJECT NO.: 292.11.31			

REFERENCE *Greene County Auditors, Orthophotograph (1998); State Plane Coordinates from Woolpert Surveying, LLP, Dayton, Ohio (NAD83/NAVD88)*

TABLES

Table 1: Model Calibration Results for Each Target Value

Monitoring Well ID	Measured Values (March 2004)	Model Predicted Values	Residual Error
CW01-01	1005.55	1005.46	0.09
CW01-02	1006.03	1006.112255	-0.0822554
MW01-01	1021.63	1021.581386	0.0486142
MW01-04	1019.38	1019.28301	0.0969897
MW01-04CD	1019.35	1019.390158	-0.0401583
MW01-04SE	1019.99	1019.272123	0.717877
MW01-09	1016.78	1016.346243	0.433757
MW01-10	1014.01	1014.727743	-0.717743
MW01-11	1021.77	1021.532137	0.237863
MW02-03	1019.59	1019.464277	0.125723
MW02-04	1017.89	1017.90576	-0.0157599
MW02-05	1017.38	1017.446295	-0.0662953
MW02-07	1014.58	1014.594288	-0.0142879
MW02-08CD	1018.65	1018.74781	-0.0978104
MW02-08SE	1018.84	1018.749376	0.090624
MW02-10CD	1013.59	1013.415106	0.174894
MW02-11	1018.67	1018.045385	0.624615
MW02-11SE	1017.52	1018.05731	-0.53731
MW02-15	1012.07	1012.014039	0.0559615
MW02-16	1012.64	1013.245031	-0.605031
MW02-17	1017.59	1017.689093	-0.0990929
MW02-17CD	1017.62	1017.681436	-0.061436
MW02-18	1019.75	1019.827013	-0.0770127
MW02-18CD	1019.76	1019.813496	-0.0534962
MW01-02	1022.5	1022.712244	-0.212244
MW01-02CD	1022.61	1022.708698	-0.0986975
MW01-02SE	1022.7	1022.99045	-0.29045
MW01-03	1021.98	1021.887508	0.0924925
MW01-03CD	1021.79	1021.93583	-0.14583
MW01-05	1018.21	1018.11547	0.0945298
MW01-05CD	1016.86	1017.641948	-0.781948
MW01-06	1022.01	1021.979316	0.0306842
MW01-07	1023.53	1023.375062	0.154938
MW01-08	1023.6	1023.488447	0.111553
MW01-14	1017.53	1017.560487	-0.0304874
MW02-01	1021.3	1021.467713	-0.167713
MW02-02	1019.6	1019.763781	-0.163781
MW02-03CD	1019.44	1019.473826	-0.0338256
MW02-03SE	1019.24	1019.454667	-0.214667
MW02-04CD	1017.85	1017.832305	0.0176951
MW02-05CD	1017.54	1017.50316	0.0368399
MW02-06	1016.42	1016.418797	0.00120272
MW02-08	1018.74	1018.776966	-0.0369657
MW02-09	1014.22	1014.231583	-0.011583
MW02-10	1013.15	1013.362328	-0.212328
MW02-13	1019.45	1019.471583	-0.0215825
MW02-14	1018.14	1018.198237	-0.0582374
MW02-14CD	1018.24	1018.17641	0.0635897
MW02-15CD	1011.92	1011.971842	-0.0518419
MW02-16CD	1013.95	1013.335159	0.614841
RW01-05	1021.79	1021.11681	0.67319

ATTACHMENTS