GROUNDWATER FLOW MODEL AND REMEDIAL SYSTEM DESIGN REPORT

UNC Chapel Hill, Airport Road Waste Disposal Area, Chapel Hill, North Carolina

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1 INTRODUCTION

ARCADIS was retained by the University of North Carolina at Chapel Hill to analyze aquifer tests, and to develop a groundwater flow model to evaluate remedial scenarios at the Airport Road Waste Disposal Area in Chapel Hill, NC. This report describes the construction and calibration of the groundwater flow model and presents modeling results for a remedial system designed to contain the constituent plumes observed at the site. A summary of the groundwater constituent sources and previous environmental investigations of this site can be found in the Remedial Investigation Report (ARCADIS, 2004).

Figure 1-1 shows the site location, near Highway 86 (Airport Road) and the Horace Williams Airport in Chapel Hill, Orange County, North Carolina. The source of constituents is a small sequence of burial trenches referred to as the Airport Road Waste Disposal Area. This source is near the surface water divide on the south side of a small, sloping, wooded watershed that forms a branch of Crow Branch Creek. Monitoring wells have been installed around the source area, and constituents have been detected in the groundwater between the source and Crow Branch Creek to the north. The region including the source area and all monitoring wells is collectively referred to as 'the site' in this report. More details on the site location and geometry can be found in the Remedial Investigation Report (ARCADIS, 2004).

2 AQUIFER TEST ANALYSIS

In preparation for the design and analysis of a groundwater recovery remedial system, two pumping tests were conducted. One of the pumping tests recorded drawdown data in several observation wells during pumping and recovery of a deep (80 ft) well labeled DRW-1. The other test collected drawdown data in several observation wells during vacuum-enhanced recovery in a shallow (25 ft) well labeled VER-1. The DRW-1 test was conducted on May 6-7, 1998, and the VER-1 test was conducted on April 30, 1998.

2.1 ANALYSIS METHOD

The data from both pumping tests were analyzed using AQTESOLV for Windows (HydroSOLVE, 1996), a widely accepted software package designed for the analysis of various types of aquifer tests. AQTESOLV estimates aquifer parameters by matching or calibrating the curve plotted from an analytical equation using these parameters to the observed drawdown vs. time data. Curve fitting can be done visually or automatically, using an optimization algorithm to minimize the sum of squared residuals (simulated displacement minus observed displacement). A variety of equations based on different conceptual models of an aquifer are available. The most appropriate equation to use for a given test depends on the aquifer geometry and properties of the subsurface media, which are typically not known in detail. Therefore, an aquifer test can be analyzed using multiple equations, and the fit quality of these different curves compared with each other to draw inferences about the aquifer's behavior. The estimated parameter values are often fairly insensitive to the choice of analytical equation. For example, if two different equations were fitted to the same data, one assuming porous media and the other assuming fractured media, the fit quality of one curve might be superior to the other, while both analyses yield similar values of hydraulic conductivity and the storage coefficient.

2.2 DRW-1 PUMPING TEST ANALYSIS

The pumping test in DRW-1 removed water at a rate of five gallons per minute for 1448 minutes, after which water levels were allowed to recover without pumping. Water level data were collected during the drawdown and recovery phases from DRW-1 and several observation wells. Among the observation wells for which data were available, six wells were selected (in addition to DRW-1) because the responses in these wells were significant enough to yield meaningful calibrations. Since the observation wells exhibited a variety of responses, a separate displacement vs. time analysis was conducted for each observation well, rather than combining data from different wells to conduct a single displacement vs. distance analysis.

The static water table was assumed to be at the DRW-1 land surface elevation (461.5 fmsl) in all DRW-1 analyses. Since static water level data were not available for DRW-1, this assumption was based on the observation that DRW-1 is a flush-mounted well and is periodically artesian with a low discharge rate. The saturated aquifer thickness was assumed to be 80 feet because DRW-1 is an open bedrock well reaching a depth of 80 feet. The one exception is the analysis for observations in MW-14, which assumed a saturated thickness of 154.8 feet because MW-14 penetrates the bedrock to a depth this far below the DRW-1 land surface elevation. Partial penetration of observation wells was accounted for in the Theis (1935) analyses.

Table 2-1 summarizes the values of the hydraulic conductivity and storage coefficient estimated from these analyses, as well as the analytical equation used in each analysis. Figures showing the AQTESOLV output for each analysis are included in Appendix A. All of these DRW-1 analyses used automatic least-squares calibration. The calibrations were highly sensitive to the estimated hydraulic conductivity values, which ranged over less than a factor of two (from 0.1296 ft/d to 0.2344 ft/d) among the seven different analyses. In contrast, the storage coefficient values were relatively insensitive (poorly constrained by these calibrations). They ranged over more than four orders of magnitude (from 0.0000111 to 0.4042).

For all observation wells, the Theis (1935) solution for an unconfined aquifer provided a closer match to the observed data than the other analytical solutions available in AQTESOLV. The data from the pumping well, however, was fit better by the Moench (1984) solution for a fractured aquifer composed of slab-shaped blocks. This equation approximates the aquifer using a double-porosity system consisting of low-permeability (primary porosity) blocks and high-permeability (secondary porosity) fissures. It does not consider the effects of partially penetrating wells and assumes that the aquifer is homogeneous and of uniform thickness. The fracture spacing used in the Moench Slab Fracture analysis of DRW-1 data was based on the linear average of spacing between fractures reported in the drilling log for DRW-1. For comparison, analyses of the DRW-1 displacement data using both the Theis (1935) and Moench (1984) solutions are included in Table 2-1 and the AQTESOLV output figures in Appendix A.

2.3 VER-1 PUMPING TEST ANALYSIS

The pumping test in VER-1 applied a vacuum equivalent to about 25 inches of mercury to test the feasibility of vacuum-enhanced recovery in the shallow saprolite overlying the bedrock. The water recovery rate was approximately 3.3 gallons per minute during the early part of the test before a high vacuum was established. Based on this approximate pumping rate, AQTESOLV was used to analyze data from the drawdown portion of the test for six different observation wells. As with the DRW-1 pumping test, a drawdown vs. time curve was fitted separately for each observation well. The resulting aquifer parameter estimates are given in Table 2-2. Data from each well were analyzed twice, once with the unconfined Theis (1935) equation and once with the Moench (1984) equation for fractured rock with spherical blocks. Only the Theis (1935) analyses accounted for partial penetration of observation wells. All analyses used automatic parameter estimation. Although this pumping test was conducted and observed in wells screened above the bedrock, the slab fracture solution appears to fit the observed data better than the unconfined Theis (1935) equation does. Both solutions fit the observed data closely for all six tests, and the average estimated hydraulic conductivity only varies by 25% between these two analysis methods. The AQTESOLV output figures for the VER-1 test are included as Appendix B.

2.4 AQUIFER TEST CONCLUSIONS

A fractured media solution provided the best fit for the data from DRW-1 itself, while a porous media solution provided a better fit for the observation wells used in the DRW-1 pumping test. This apparent contradiction is probably due to the different spatial scales reflected in data from observation wells versus data from the test well. Water levels in DRW-1 during the test resulted from the behavior of the aquifer media extending only a few bore hole radii, whereas water levels in observation wells resulted from aquifer behavior over the distance between the test well and the observation well. Since DRW-1 and the observation wells are known to be located in fractured bedrock, the apparently different aquifer behavior reflected in the DRW-1 data merely confirms that fractured media can be accurately modeled as porous media for applications relevant to distances equal to or exceeding the distance between wells.

Since observed water levels are far more precise and meaningful measurements than parameters estimated from aquifer tests, the aquifer parameters used in the final groundwater flow model were estimated from calibration of the model to the observed water levels and groundwater flow directions inferred from the observed constituent plumes. Nevertheless, aquifer tests provided parameter values for use as initial estimates prior to calibration of the groundwater flow model, and as guides for judging the reasonable variation of parameter values to use in the calibrated model.

3 CONCEPTUAL MODEL OF GROUNDWATER FLOW

Prior to the development of a mathematical groundwater flow model, it is necessary to develop a conceptual model of subsurface conditions that summarizes important geologic, hydrologic, and hydraulic features of the groundwater system. This conceptual model will provide the framework that describes essential input parameters required by a mathematical model. Thus, the understanding of the groundwater system developed in a conceptual model is the foundation for a mathematical model.

A conceptual groundwater flow model succinctly describes the principal components of a groundwater flow system and is developed from regional, local, and site-specific data. The primary components of groundwater flow systems include: (1) areal extent, configuration, and type of aquifers and aquitards; (2) hydraulic properties of aquifers and aquitards; (3) natural groundwater recharge and discharge zones; (4) anthropogenic groundwater sources and sinks; and (5) areal and vertical distribution of groundwater hydraulic head potential.

3.1 PHYSIOGRAPHY

The site lies within the Piedmont Plateau Physiographic Province. The Piedmont Plateau is an ancient erosional surface characterized by gently rolling well-rounded hills and long low ridges. The Piedmont Plateau is 60 to 75 miles wide and ranges in altitude from 500 to 1,500 feet. The topography is consistent with this characterization in the vicinity of the UNC Site, with rolling hills incised by many streams. Drainage in the Piedmont Plateau is generally toward the southeast because of the general northwest-southeast orientation to the stream valleys. The stream valleys are generally aligned with structural features in the underlying bedrock.

The site is located slightly north of center on a broad ridge that forms the south side of a small watershed draining into a fork of Crow Branch Creek. The site is about half way between the head of the watershed to the west and the mouth of the watershed to the east. As with most well-incised watersheds of high stream order in the Piedmont physiographic province, the ridges forming the sides of the watershed slope steeply downward toward the stream to which the fork draining the watershed is a tributary, but this slope levels out about half way between the mouth and the head of the watershed. The site is located at the eastern end of this relatively flat reach of the ridge, close to the point where the ridge descends steeply to the east toward the main branch of Crow Branch Creek.

3.2 GEOLOGY

In the vicinity of the UNC Site there are two discrete lithologic units; a surficial regolith and a bedrock complex. The surficial unit consists of unconsolidated soil and saprolite material. The saprolite is primarily residual soil derived from in-situ weathering of the underlying rock. Drilling logs from the monitoring wells indicate that the regolith is dominated by silty clay with varying amounts of organic matter and detritus and occasional localized deposits of quartz sand.

Granite and diorite bedrock underlies the surficial regolith at a depth ranging from zero to 25 feet (based on drilling logs from the site). This contact is gradational, since it was formed by the downward advancement of a weathering front into the bedrock. The bedrock is generally massive, with abundant high-angle fractures. The average spacing of fractures large enough to be noted in the monitoring well drilling logs was 10 feet.

3.3 HYDROGEOLOGIC FRAMEWORK

3.3.1 HYDROSTRATIGRAPHY

The water table aquifer occurs in the weathered regolith at a depth from zero to 16 feet. No areally continuous stratification of the regolith was evident from the lithologic logs of the monitoring wells, although the depth to bedrock was highly variable. Because abundant fractures were observed in the bedrock during the drilling of monitoring wells, the bedrock was expected to have a significant hydraulic conductivity. Nevertheless, the hydrologic behavior of the surface regolith and the fractured bedrock will be different because these media have such different structural compositions.

3.3.2 GROUNDWATER USAGE

No groundwater supply wells exist within the study area, nor is any remedial system currently in place at the site. An extensive discussion of regional groundwater and surface water usage can be found in the Remedial Investigation Report (ARCADIS, 2004).

3.3.3 OBSERVED WATER LEVELS

ARCADIS prepared separate water level contour maps for the surface regolith and the bedrock from sampling events (from 1995 through 2004). These water level maps consistently showed a water table gradient of roughly 0.04 ft/ ft sloping to the north-northwest toward the nearest reach of Crow Branch Creak from the source area. Potentiometric head levels in the bedrock were slightly more complex, with a northwest trending ridge of high levels between the source area and Crow Branch Creek suggesting a divergence of flow to the north and the west around an area of low permeability. Average gradients in the bedrock were comparable to those in the regolith.

3.3.4 HYDRAULIC PROPERTIES

Geraghty & Miller (1996) conducted several slug tests in both the shallow (regolith) wells and the deep (bedrock) wells. To augment the slug test results in preparation for installation of remediation wells, two pumping tests were conducted subsequent to the Geraghty & Miller (1996) remedial investigation report. The data from these pumping tests were analyzed as part of the present effort and are presented in the Aquifer Test Analysis section. The hydraulic conductivities estimated from these two pumping tests can be compared with those determined by the former slug tests. The average conductivity from slug tests in those wells screened above the bedrock was 1.508 ft/d. This value is between the averages from the Theis (1935) and Moench (1984) solutions for the VER-1 test (Table 2-2). The average conductivity from slug tests in bedrock wells was 12.08 ft/d, which is nearly two orders of magnitude higher than the average value from the DRW-1 pump test. This disagreement may be due to the fact that early time data were emphasized over later time data in the slug test analyses.

3.3.5 GROUNDWATER-SURFACE WATER INTERACTIONS

Shallow groundwater in the areas where constituents have been detected is within the watershed of Crow Branch Creek and is flowing toward the creek. No standing surface water exists near the site, due to the eroded hilly topography.

4 GROUNDWATER FLOW DIRECTIONS

Both the observed water levels and the observed constituent plumes indicate that groundwater beneath the disposal area is moving generally to the north and northwest toward the nearest reach of Crow Branch Creek. From the water level maps in the Remedial Investigation Report (ARCADIS, 2004), it appears that flow in the bedrock is directed slightly more to the north and northeast than flow in the shallow regolith. This is consistent with the expectation that deeper flow directions would reflect larger-scale flow systems, in this case the flow from the head of the watershed towards its mouth. The observed water levels in deep wells also suggested a low-conductivity zone directly between the disposal area and Crow Branch Creek that could potentially divert flow to the east and west and cause plume spreading beyond that due to dispersion.

4.1 CONCEPTUAL MODEL OF CONSTITUENT FATE AND TRANSPORT

The Remedial Investigation Report (ARCADIS, 2004) provided a list of constituents that might be found at the site, based on records of what was placed in the disposal facility. Although this list includes many compounds, 26 of which were detected in groundwater at the site, the primary constituents known to exist in several down-gradient wells at concentrations clearly elevated above background are the following volatile organic compounds: benzene, chloroform, diethyl ether, and methylene chloride. The distribution of these constituents in groundwater at the site is primarily a function of the rate of leaching from the disposal area as well as groundwater flow directions and velocities. Constituent fate and transport is also affected by the natural attenuation processes of adsorption and degradation, as well as concentration decrease via precipitation recharge.

4.2 FLOW DIRECTIONS INFERRED FROM OBSERVED CONSTITUENT DISTRIBUTIONS

Dissolved constituents have been found in several wells between the disposal area and the nearest reach of Crow Branch Creek, and at depths from the water table to 174 feet. The large vertical thickness of the plume clearly indicates a moderate vertical component of constituent transport, and therefore of groundwater flow.

The highest total VOC concentrations observed in the surface regolith aquifer occur in monitoring wells MW-1 and MW-2 just across the road to the northwest of the disposal area. This suggests that the groundwater recharging through the disposal area flows horizontally at least as far as these two wells before it flows downward into the bedrock and is replaced in the shallow aquifer by further recharge between the disposal area and Crow Branch Creek. The other shallow peak in total VOC concentrations occurred in monitoring well MW-12 near the creek. This probably indicates upward flow near the creek. Thus, the observed total VOC concentrations in the shallow aquifer suggest a conceptual model in which the plume is transported by groundwater recharging at the source area, flowing horizontally toward the nearest reach of the creek and downward into the bedrock, and then flowing back upward to discharge at the creek.

The peak observed total VOC concentration in the deep wells occurred in MW-15 near Crow Branch Creek. Other high concentrations detected in monitoring wells MW-13 and MW-11 along a line to the northeast of MW-15 suggest transport in that direction. No deep well data exists close to the source area. The total VOC plume observed in the deep wells suggests the plume is being transported toward Crow Branch Creek. Groundwater flow and concentration data suggest another component of the plume is migrating parallel to the creek in the down valley direction. Some constituent plumes travel as far east as MW-31. This plume transport is likely due to the variable nature of the permeability and structure of the bedrock. Additionally, deep bedrock well data for one of the compounds, diethyl ether, suggests that the plume is actually passing under Crow Branch Creek. This is evident in elevated concentrations of diethyl ether in MW-33 which is located due north of the waste disposal area on the northern side of Crow Branch Creek.

5 GROUNDWATER FLOW MODEL CONSTRUCTION

The modeling tool is selected after development of a conceptual model. The conceptual model of groundwater flow is used to determine initial values for all model parameters and to assess the necessary resolution of model discretization and the necessary extents of the model grid. Boundary conditions and zones with different parameter values are then added to the model. The final zonation or distribution of parameters, and sometimes even the boundary conditions and the model discretization, are adjusted during model calibration.

Calibration is the iterative process of changing the model and/or its parameters so that the simulated water levels and flow directions match as closely as possible with the corresponding observed values. Grid spacing was not changed during the calibration of the UNC model, and the boundary conditions and layer bottom elevations were only slightly refined. Therefore, these model features will be discussed within this section on model construction. Other parameters, however, including hydraulic conductivities and recharge – were modified from the initial values during model calibration. These parameters will be discussed in the section on model calibration.

5.1 GROUNDWATER FLOW CODE SELECTION AND DESCRIPTION

For the simulation of groundwater flow at the UNC site, ARCADIS utilized the code MODFLOW, a publicly available groundwater flow simulation program developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988). MODFLOW is thoroughly documented, widely used by consultants, government agencies and researchers, and is consistently accepted in regulatory and litigation proceedings. Given the intended use for the UNC groundwater flow model as a remedial decision-making tool, regulatory acceptance is vital for the code selected for this study.

In addition to its attributes of widespread use and acceptance, MODFLOW was also chosen because of its versatile simulation features. MODFLOW can simulate transient or steady-state saturated groundwater flow in one, two, or three dimensions and offers a variety of boundary conditions including specified head, areal recharge, injection or extraction wells, evapotranspiration, drains, and rivers or streams. Aquifers simulated by MODFLOW can be confined or unconfined, or convertible between confined and unconfined conditions. For the UNC site, which consists of a multi-layered geologic system with variable unit thicknesses and boundary conditions, MODFLOW's three-dimensional capability and boundary condition versatility are essential for the proper simulation of groundwater flow conditions.

MODFLOW simulates transient, three-dimensional groundwater flow through porous media described by the following partial differential equation for a constant density fluid:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad (5\text{-}1)$$

K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity [L/T]
h is the potentiometric head [L]
W is a volumetric flux per unit volume and represents sources and/or sinks of water [1/T]
S_s is the specific storage of the porous material [1/L]
t is time [T] .

In Equation 5-1, the hydraulic parameters (i.e., K_{xx}, K_{yy}, K_{zz} and S_s) may vary in space but not in time; the source/sink (W) terms may vary in both space and time.

MODFLOW uses a numerical approximation technique known as the method of finite differences to solve Equation 5-1 on a computer. Using a block-centered finite-difference approach, MODFLOW replaces the continuous system represented in Equation 5-1 by a set of discrete points in space and time. This process of discretization ultimately leads to a system of simultaneous linear algebraic equations. MODFLOW solves these finite-difference equations with one of the following three iterative solution techniques: strongly implicit procedure (SIP), slice-successive over-relaxation (SSOR), or preconditioned conjugate gradients (PCG). The solution of the finite-difference equations produces time-varying values of head at each of the discrete points representing the real aquifer system. Given a sufficient number of discrete points, the simulated values of head yield close approximations of the head distributions given by exact analytical solutions to Equation 5-1.

5.2 THE STEADY-STATE FLOW ASSUMPTION

The steady-state flow assumption was used for the UNC groundwater flow model. Transient (time variant) groundwater flow simulation is sometimes necessary in cases where natural (e.g., seasonal) cycles in boundary conditions such as the recharge rate may impact modeling conclusions, or when anthropogenic sources or sinks change the boundary conditions over the time scale of interest. In the present case, however, no anthropogenic groundwater sources or sinks have significantly affected the regional flow system in the past, and none are likely in the future. Furthermore, the time scale of interest is several years, over which natural annual cycles can be approximated with average boundary conditions.

5.3 HORIZONTAL GRID SIZE AND SPACING

The finite-difference technique employed in MODFLOW to simulate hydraulic head distributions in multi-aquifer systems requires horizontal and vertical discretization or subdivision of the continuous aquifer system into a set of discrete blocks that form a three-dimensional model grid. In the block-centered finite-difference formulation used in MODFLOW, the center of each grid block corresponds to a computational point or node. When MODFLOW solves the set of linear algebraic finite-difference equations for the complete set of blocks, the solution yields values of hydraulic head at each node in the three-dimensional grid.

Water levels computed for each block represent an average water level over the volume of the block. Thus, adequate discretization (i.e., a sufficiently fine grid) is required to resolve features of interest, and yet not be computationally burdensome. MODFLOW allows the use of variable grid spacing so that a model may have a finer grid in areas of interest where greater accuracy is required and a coarser grid in areas requiring less detail. The full model grid developed for the UNC site covers approximately 1.8 square miles (Figure 5-1). The boundaries of the model grid are specified to coincide with natural hydrogeologic boundaries and to minimize the influence of model boundaries on simulation results at the site. The three-layer finite-difference grid is composed of 180 columns and 180 rows, for a total of 97,200 nodes. The model grid uses 10 ft horizontal spacing in the area of the constituent plumes to provide increased computational detail and grades to 100 ft horizontal spacing at the perimeter of the grid.

The extent of the finite-difference grid and the region of fine horizontal discretization used on-site were selected for the purpose of simulating both regional and site-scale groundwater flow conditions. The extent chosen for the grid ensured adequate incorporation of regional groundwater flow features that affect conditions at the site. The horizontal grid spacing specified near the site allowed a sufficiently detailed simulation of hydraulic heads to match measured water levels and groundwater flow directions. Meeting both of these objectives was essential for the calibration of the groundwater flow model.

The water table at the UNC site occurs in the surficial regolith, but the groundwater flow system extends deep into the crystalline bedrock. As expected in a typical steep piedmont terrain of weathered igneous and metamorphic rock, flow directions have a downward component near ridges (where recharge occurs) and an upward component near streams (where discharge occurs). This conceptual model was confirmed at the UNC site by four lines of evidence: observed vertical gradients, observed constituents at a depth of 174 ft beneath the site (ARCADIS, 2004), observed artesian conditions in the bedrock near Crow Branch Creek, and results of calibrating the model to observed heads in monitoring wells. To accurately simulate this deep flow system, the model was extended to a depth averaging 195 feet below land surface, corresponding with the depth to which fractures with significant permeability are thought to extend in typical piedmont bedrock (ARCADIS, 2004).

5.4 LAYER BOTTOM ELEVATIONS

The primary reason to include vertical discretization (multiple layers) in a groundwater flow model is to capture the differences in hydrogeologic behavior (aquifer parameters) between different strata with different lithologies and to simulate vertical gradients.

The UNC model included three layers. In the off-site area of the model (all regions outside the area with monitoring wells), the bottom of model Layer 1 was intended to roughly correspond with the contact beween regolith and bedrock. Bottoms were set 15.57 ft below land surface. This depth was the average depth to bedrock in the drilling logs from the monitoring wells.

On site (within the region containing monitoring wells), model Layer 1 bottom elevations were set either at the bedrock surface in individual wells, or at the bottom of the well screen (for wells in model Layer 1), whichever was deeper. Since monitoring wells were roughly distributed into three depth ranges (shallow, intermediate, and deep), the model layer in which each well belonged was chosen before the model layer bottoms were set. Thus, vertical spacing of the wells helped to define the choices of model layer bottoms.

The bedrock was further divided into two model layers to provide increased vertical resolution for simulating flow directions and partial penetration of postulated recovery wells. Since the elevation of the contact between these model layers was not based on lithology, it was placed roughly between the wells of intermediate depth and the deepest wells. The bottom elevations for model Layer 2 were set at a constant 59.43 ft below the model Layer 1 bottoms throughout the model domain, making the contact between model Layers 2 and 3 exactly 75 ft below land surface in the off-site areas. Similarly, the bottoms of model Layer 3 were set a constant 120 ft below the bottoms of model Layer 2 throughout the model domain.

5.5 BOUNDARY CONDITIONS

Boundary conditions must be imposed to define the spatial boundaries of the model on the top, bottom, and all sides of the model grid. In addition to these boundary conditions, sources and sinks of groundwater such as wells and rivers can be included within the model's external boundaries. A boundary condition can represent different types of physical boundaries, depending on the rules that govern groundwater flow across the boundary. The UNC model includes four types of boundary conditions: no-flow, recharge (constant flux), drains (head-dependent outflow), and rivers (head-dependent outflow and inflow).

The entire model grid represents a rectangular solid in space, roughly 1.5 miles east-west by 1.2 miles north-south by 195 feet thick. The bottom of the grid is a no-flow boundary (a boundary across which no groundwater enters or leaves the model). The top of the model is bounded by a recharge boundary condition, which requires water to enter the model through the highest active cell at a fixed rate. In the UNC model, a single recharge rate of 7 inches per year occurs over the whole model area. This recharge rate was determined during model calibration.

Figure 5-1 shows the finite difference grid and all boundary conditions in model Layer 1 for the entire model. Figure 5-2 shows the same features but at a scale zoomed in on the site. Model Layers 2 and 3 contain no boundary conditions other than the no-flow cells defining the limits of the active grid area, and these no-flow cells occupy the same positions in all three model layers. To produce the most accurate simulation possible, it is generally necessary to extend a model's horizontal boundaries to include natural hydrogeologic divides, because the local flow system at the site includes components controlled by the surrounding regional flow system. Regional flow components would be lost from the simulation if arbitrary boundary conditions were imposed close to the site in order to use a smaller model grid. Defining arbitrary boundary conditions close to the UNC site would also have introduced more calibration parameters, since significant horizontal groundwater flow would occur across such boundaries, and no natural data would exist with which to estimate these boundary flows. The time consumed by these excess fitting parameters during model calibration would more than offset any gains in runtime achieved through using a smaller grid.

Because of the relative impermeability of deep crystalline bedrock, groundwater flow is normally confined to a few hundred feet below land surface. Therefore, groundwater flow systems tend to be localized, and groundwater divides reflect surface water divides. Except for the southeast corner of the UNC model, all horizontal boundaries of the active grid region are composed of no-flow cells representing groundwater divides beneath topographic highs (where no horizontal flow occurs because flow is directed downward). These boundaries allow the active model area to include the entire watershed of the branch of Crow Branch Creek passing by the site. At the southeast corner of the model, the active grid area extends beyond this watershed to the first groundwater divide to the south, which is a topographic low where groundwater flows upward, probably discharging to an intermittant stream. This extension of the active model area was included because the Airport Road Waste Disposal Area is very close to the topographic high on the south side of the Crow Branch Creek watershed; thus, simulation of groundwater flow on the other side of the divide is necessary to precisely simulate conditions on the site.

Intermittant or perennial stream boundaries were simulated by placing “drain” or “river” cells along the streams. Drains allow groundwater to discharge, as long as the groundwater level in a drain cell is higher than the specified drain elevation, but do not allow groundwater recharge. In contrast, river cells allow either discharge or recharge, depending on whether the simulated groundwater elevation in the river cell is above or below the specified surface water level. Rivers were used to simulate the branch of Crow Branch Creek passing by the site, up to the small wetland shown on the site base map. Drain cells were used to represent the steeper reach of Crow Branch Creek from the wetland area to the head of the watershed. Drains were also used to simulate all tributaries of Crow Branch Creek and the topographic low along the southeast model boundary.

6 GROUNDWATER FLOW MODEL CALIBRATION

6.1 CALIBRATION APPROACH

Groundwater flow model construction ends with the specification of all input parameters that are not typically estimated during calibration. For example, the bottom elevations in the UNC model were based on the observed topography, hydrostratigraphy, and well depth distribution, rather than their effect on the calibration. Calibration begins with the specification of initial estimates for the hydraulic parameter values and zonation (spatial regions containing different values). Model calibration is the laborious and iterative process of making small or large changes to the model and its input parameter values and re-running the model until the simulation results closely match conditions observed at the site. Before this process can begin, the calibration objectives must be defined in the form of a set of observed data referred to as calibration "targets". Then the calibration can be carried out partially with automatic optimization algorithms that re-run a simulation until an optimum input parameter value is found that results in a satisfactory model calibration within the realm of parameter values dictated by the conceptual model. Once calibration is complete, statistical methods can be used to express the goodness of fit to the calibration targets, and a sensitivity analysis can be conducted to determine which input parameter values are most important and the level of confidence associated with each value.

The principle of input parameter parsimony was applied to achieve an adequate calibration of the model through the use of the fewest number of model parameters. It should be noted that adding more input parameters than necessary during model calibration creates a situation in which many combinations of model parameter values produce similar calibration results. In this case, the model calibration parameters are called nonunique. Following the principal of parameter parsimony reduces the degree of nonuniqueness and results in more reliable calibrated parameter values. The information gathered for the conceptual model guides any decision to add model parameters (e.g., zones of hydraulic conductivity) to the model during the calibration process. Therefore, in the absence of hydrogeologic evidence, the simpler model is preferred.

6.2 CALIBRATION OBJECTIVES

The first step in calibrating a groundwater flow model is to identify and collect data for calibration "targets". The targets are data that can be both measured in the field and predicted by the model. When the model is calibrated, the predicted data values will closely match the observed values, within some statistically defined tolerance. In principle, the targets can include any combination of data at several different spatial points around the site, for example, water levels in monitoring wells. Ideally, the simulated values of these data should be highly sensitive to the input parameters being estimated during the calibration. In practice, the calibration targets usually consist of a set of water levels from monitoring wells. For best results, the calibration of a model should rely on discrete measurements to produce answers free of contouring interpretations. In the calibration of a groundwater flow model, use of point data eliminates the potential for interpretive bias that may result from attempting to match a contoured potentiometric surface (Konikow, 1978; Anderson and Woessner, 1992).

The targets used for calibrating the UNC groundwater flow model included 31 water levels collected on July 19, 2004 from monitoring wells at different depths around the site. Table 6-1 shows the observed and simulated water levels used in the calibration, along with the calibration residuals (observed minus simulated levels).

A critical calibration constraint in the UNC model was the observed distribution of constituents. Unfortunately, simulating flow directions consistent with the observed plumes required some parameters and zones that did not provide an optimum fit to observed water levels, as reflected in the flow model sensitivity analysis. This kind of conflict between calibration objectives is a common occurrence during calibration of three-dimensional groundwater flow models in complex piedmont terrain, and it requires a compromise between statistical fit quality, model simplicity, and realism.

6.3 STATISTICAL CALIBRATION PROCEDURE

ARCADIS routinely uses a proprietary automatic parameter estimation program to calibrate groundwater flow models. Starting with a set of initial estimates for the model parameters, the program systematically updates the parameter estimates to minimize the difference between simulated and observed water levels at a set of calibration targets. Compared to trial and error procedures for model calibration, automatic parameter estimation can greatly reduce the time required for model calibration and generally provide a better overall calibration. The general algorithm applied in conjunction with the MODFLOW code is known as the Gauss-Newton method and is described in greater detail by Hill (1992).

The primary criterion for evaluating the calibration of a groundwater flow model is the difference between simulated and observed water levels at a set of calibration targets. A residual or model error, e_i, is defined as the difference between the observed and simulated hydraulic head measured at a target location:

$$e_i = \hat{h}_i - h_i \tag{6-1}$$

where h_i is the measured value of hydraulic head and $\hat{h}_i$ is the simulated value at a specific target location. A residual with a negative sign indicates underprediction by the model (i.e., the simulated head is lower than the measured value). Conversely, a positive residual indicates overprediction.

The automatic parameter estimation procedure seeks to minimize an objective function defined by the residual sum of squares (RSS):

$$RSS = \sum_{i=1}^{n} \left(h_i - \hat{h}_i\right)^2 \tag{6-2}$$

where n is the total number of calibration targets. The RSS is the primary measure of model fit. The residual standard deviation (RSTD), which normalizes the RSS by the number of calibration targets and number of estimated parameters (p), is defined as follows:

$$RSTD = \sqrt{\frac{RSS}{n - p}} \tag{6-3}$$

The RSTD is useful for comparing model calibrations with different numbers of calibration targets and estimated parameters. Another calibration measure is the mean of all residuals ($\bar{e}$):

$$\bar{e} = \frac{1}{n} \sum_{i=1}^{n} e_i \tag{6-4}$$

A mean residual significantly different from zero indicates model bias. The Gauss-Newton parameter estimation procedure produces a near zero mean residual at the minimum RSS.

6.4 ANALYSIS OF RESIDUALS

Table 6-1 presents the residuals from the calibrated UNC groundwater flow model. Figure 6-1 shows a plot of the observed vs. simulated water levels. If the calibration were statistically perfect, all points on this plot would lie along the solid diagonal line.

The two dashed lines denote the boundaries of the data range that includes simulated water levels within plus or minus 10% of the observed variability across the site from the corresponding observed water level. The calibration procedure typically continues until all targets are within or close to this 10% range, as shown in Figure 6-1. The statistical closeness of the final calibration depends on many factors, however, including the complexity of the simulated terrain, the quantity and quality of target values, and other calibration objectives that may aid or compete with the statistical fit. In the present analysis, calibrating to a smaller sum of squared residuals (RSS) would have required a combination of arbitrary zonation and unrealistic parameter values. It would also have violated the groundwater flow directions inferred from the observed constituent plumes.

6.5 ESTIMATED INPUT PARAMETERS

Each input parameter value pertains to a spatial zone, which is defined as the set of grid cells with that particular parameter value. The parameter values used in the UNC groundwater flow model are summarized in Table 6-2.

Whereas recharge was included as just one zone covering the entire model with a value of 7 inches per year, hydraulic conductivity included seven zones. The locations of these zones are shown in Figures 6-2 through 6-4 for model Layers 1 through 3, respectively. Zone 1 (K = 1.25 ft/d) corresponds to the western half of model Layer 1. Physically, it corresponds to the soil and weathered regolith found near the land surface in upland areas. Zone 2 (K = 0.1 ft/d) covers the eastern half of model Layer 1. Physically this corresponds to a more resistant rock than Zone 1. Zone 3 (K = 0.35 ft/d) extends throughout most of model Layers 2 and 3 and physically corresponds to the fractured bedrock.

Zone 4 (K = 10 ft/d) occurs along the lower reaches of Crow Branch Creek in all three model layers. This relatively high-conductivity zone is physically consistent with the fact that streams incising crystalline bedrock often form along areas of extensive fracturing and structural and/or chemical weakness (Bras, 1990). Note that Zone 4 is much more extensive in model Layer 1 than it is in model Layers 2 and 3, which is consistent with the more extensive weathering in model Layer 1.

Zone 5 (K = 10 ft/d) is a high conductivity zone that occurs north of the site in model Layers 2 and 3. This zone is much tighter vertically than Zone 4 which gives it a considerably lower vertical conductance value. Zones 6 and 7 (K = 0.001 ft/d and 0.7 ft/d, respectively) are low conductivity zones that occur northeast of the site. These zones are indicated by an inflection in the observed water levels. Zones 6 and 7 may correspond to sections of bedrock that are less fractured or less weathered than the surrounding material, perhaps due to a structurally or chemically stronger composition. In addition to its role of minimizing calibration residuals, the shape of Zones 6 and 7 (and the channel running through them) was required to reproduce flow directions consistent with the observed water levels. This zonation is also consistent with a topographical lineament feature that may reflect a localized vertical fracture and weathering plane running southwest to northeast across the observed plumes just south of Crow Branch Creek (Geraghty & Miller, 1996).

6.6 SENSITIVITY ANALYSIS

Table 6-3 presents the results of a quantitative sensitivity analysis to determine which estimated input parameters have a strong impact on the simulated water levels at the target well locations. Each row of Table 6-3 illustrates the changes in the residual sum of squares (Equation 6-2) that would result from relative changes in a particular input parameter, while all other input parameters are held constant. For example, decreasing the hydraulic conductivity in Zone 6 to 80% of its chosen value would cause the RSS to decrease from 104.65 to 101.59 ft^2, whereas increasing this parameter to 120% of its chosen value would increase the RSS to 112.98 ft^2.

In a statistically ideal calibration, any perturbation of any parameter away from its chosen value (in either direction) would cause the RSS to increase. In the UNC model, raising or lowering certain parameters causes the RSS to decrease slightly, indicating that the chosen values of these two parameters are not the optimum values estimated from the statistical calibration. This is because the values of these two parameters were based on other calibration constraints (model realism and flow directions inferred from observed plumes).

6.7 SIMULATED WATER LEVELS

The regional water levels simulated by the calibrated groundwater flow model are shown in Figures 6-5 through 6-7 for model Layers 1 through 3, respectively. Figures 6-8 through 6-10 show the same simulated water levels at a scale that is zoomed in on the site area. These site-scale figures also include postings of the residual values for all the calibration targets.

The simulated water levels are the result of regional boundary conditions and flow patterns. The UNC model contains an extensive network of drains to represent all possible perennial and intermittant streams, and water levels in model Layer 1 are controlled in part by the position and elevation of these drains. This results in a water table that is a subdued reflection of land surface topography, as expected. Whereas the water table is lowered where groundwater discharges along these streams, groundwater elevations increase towards no-flow boundaries representing groundwater divides. Aside from boundary conditions, the water table shape is controlled by the zonation of hydraulic conductivity; steepened gradients occur where hydraulic conductivity is low and groundwater drains away slowly, while relatively flat areas occur where hydraulic conductivity is high and faster flow occurs.

The areas within the active grid in Figure 6-5 where the water table contours disappear are regions where the simulated water table drops below the shallow bottom of model Layer 1 into model Layer 2. In these regions, the cells in model Layer 1 become inactive (dry). Note that most of the dry areas in model Layer 1 occur near the topographic highs around the edges of the active grid, as expected. Dry areas also occur where high hydraulic conductivity allows rapid drainage of groundwater into model Layer 2 or other areas of model Layer 1.

6.8 SIMULATED GROUNDWATER FLOW DIRECTIONS

It is important to gain a qualitative understanding of the groundwater flow directions simulated by the calibrated model, since this provides the last step in developing a conceptual model of groundwater flow. As expected, flow is directed into the watershed away from the topographic highs around the perimeter of the model. The vertical component of flow is downward in the upland areas and upward near Crow Branch Creek, in agreement with the conceptual model of the regional flow system

On the site, flow is generally to the north-northwest straight toward Crow Branch Creek in model Layer 1 (Figure 6-8). In model Layers 2 and 3, however, flow is more toward the north or even the northeast (Figures 6-9 and 6-10). This is due to the influence of the larger scale regional flow system from the top of the watershed on the west toward its bottom on the east. This difference in flow directions between the upper and lower model layers is consistent with the differences in observed plume orientations.

Groundwater recharging at the Airport Road Waste Disposal Area eventually appears to discharge to Crow Branch Creek, after first descending into model Layers 2 and 3 near the source and later rising back to model Layer 1 near the creek. Additionally, flow underneath Crow Branch Creek occurs near MW-33. Simulated flow directions from the source area are consistent with the flow directions inferred from the observed constituent plumes.

7 REMEDIAL SYSTEM DESIGN

A field of groundwater recovery wells was designed to provide a remedy for the constituent plumes between the UNC Airport Road Waste Disposal Area and Crow Branch Creek. This remedial system had three primary objectives:

- Rapidly remove the groundwater with highest constituent concentrations in the shallow aquifer immediately north of the source area.
- Contain the constituent plumes in all model layers to prevent constituent discharges to Crow Branch Creek.
- Contain groundwater receiving recharge within the source area.

The first and third objectives are achieved via four shallow and closely-spaced vacuum-enhanced recovery (VER) wells across the road from the north boundary of the source area and three shallow recovery wells (SRW) located northwest of the source area along Crow Branch Creek. One of these wells corresponds to the existing VER-1 well that was used in the pumping test analysis presented above. The grid locations and simulated steady-state flow rates for these seven wells are presented in Table 7-1. The second remedial objective is achieved by three conventional deep groundwater recovery wells (DRW) that are open to the deep fractured bedrock. The grid locations and design flow rates of these three wells are given in Table 7-2.

The locations and flow rates of remedial wells were based on evaluation of the pilot tests in the VER-1 and DRW-1 wells as well as several iterations of the model with particle tracking analyses to optimize the zone of captured groundwater. For the SRW and VER wells, the pumping rates were model input values. These pumping rates were based on a balance between the need to pump fast enough for the groundwater capture zone to include the observed constituent plumes, while not simulating more discharge than the aquifer could actually yield.

Figures 7-1, 7-2, and 7-3 present a groundwater pathline analysis of the recovery system for model Layers 1, 2, and 3, respectively. These figures were generated by particle tracking (i.e., tracking the simulated trajectories of water molecules) using the USGS code MODPATH (Pollock, 1994). MODPATH was developed to be directly compatible with MODFLOW, using the MODFLOW output files as input and producing a map of the groundwater flow lines either forward or backward from a set of specified points.

Figures 7-1, 7-2, and 7-3 shows the result of a forward pathline and endpoint analysis for model Layers 1, 2, and 3, respectively. Particles were started in each of the three layers to determine the extent of the well capture zones Color filled areas depict the extent of particle capture by individual withdrawal wells. The capture zone of the four VER wells in model Layer 1 is clearly delineated by the yellow zone extending back up-gradient (southeast) from the wells. Since this capture zone includes all the groundwater in model Layer 1 beneath the source area, the VER wells are recovering all recharge that passes through the source area. Similarly, the capture zone of the three SRW wells in model Layer 1 is clearly delineated by a single red zone.

DRW-1 and DRW-2, two of the bedrock wells, are assumed to penetrate model layer 2 and are installed to an approximate depth of 80 feet below ground surface (ft bgs). The third bedrock well, DRW-3, is assumed to partially penetrate the lower bedrock layer of the model (model Layers 2 and 3) and is at a depth of at least 150 ft bgs. The capture zones of each of the three deep wells are represented by individual colors: black (DRW-1); green (DRW-2); and pink (DRW-3). The capture zones indicate that the wells provide sufficient vertical containment in the bedrock wells. Note that some of the capture zones in model Layers 2 and 3 extend on the other side of Crow Branch Creek, indicating that groundwater in these model layers is pulled beneath the creek into the recovery wells rather than flowing towards the creek.

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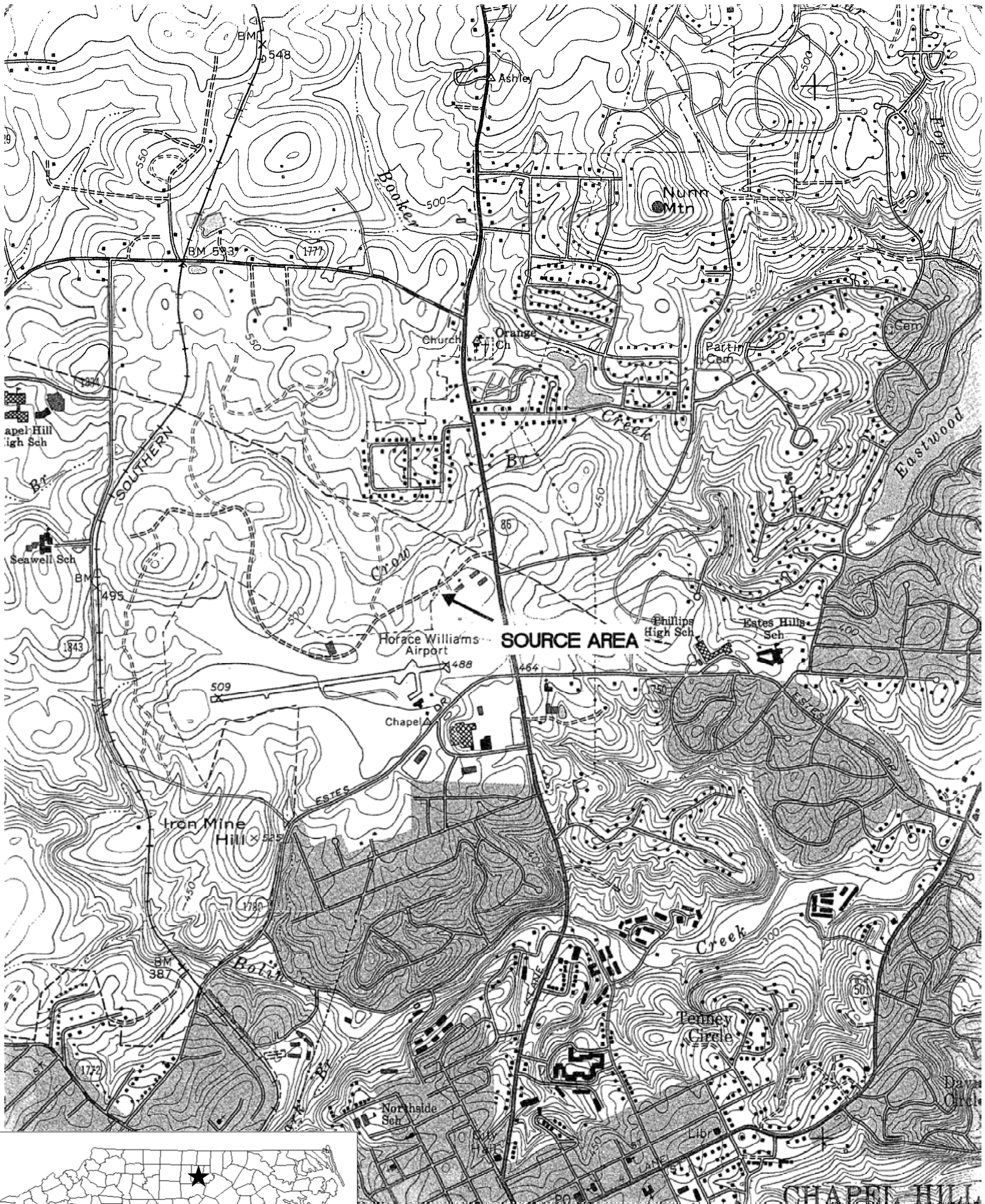
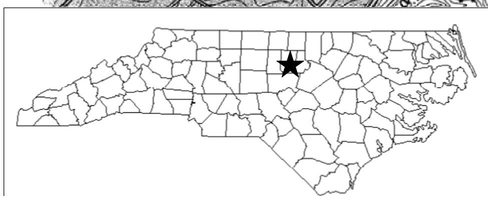
Figures





CHAPEL HILL, NORTH CAROLINA

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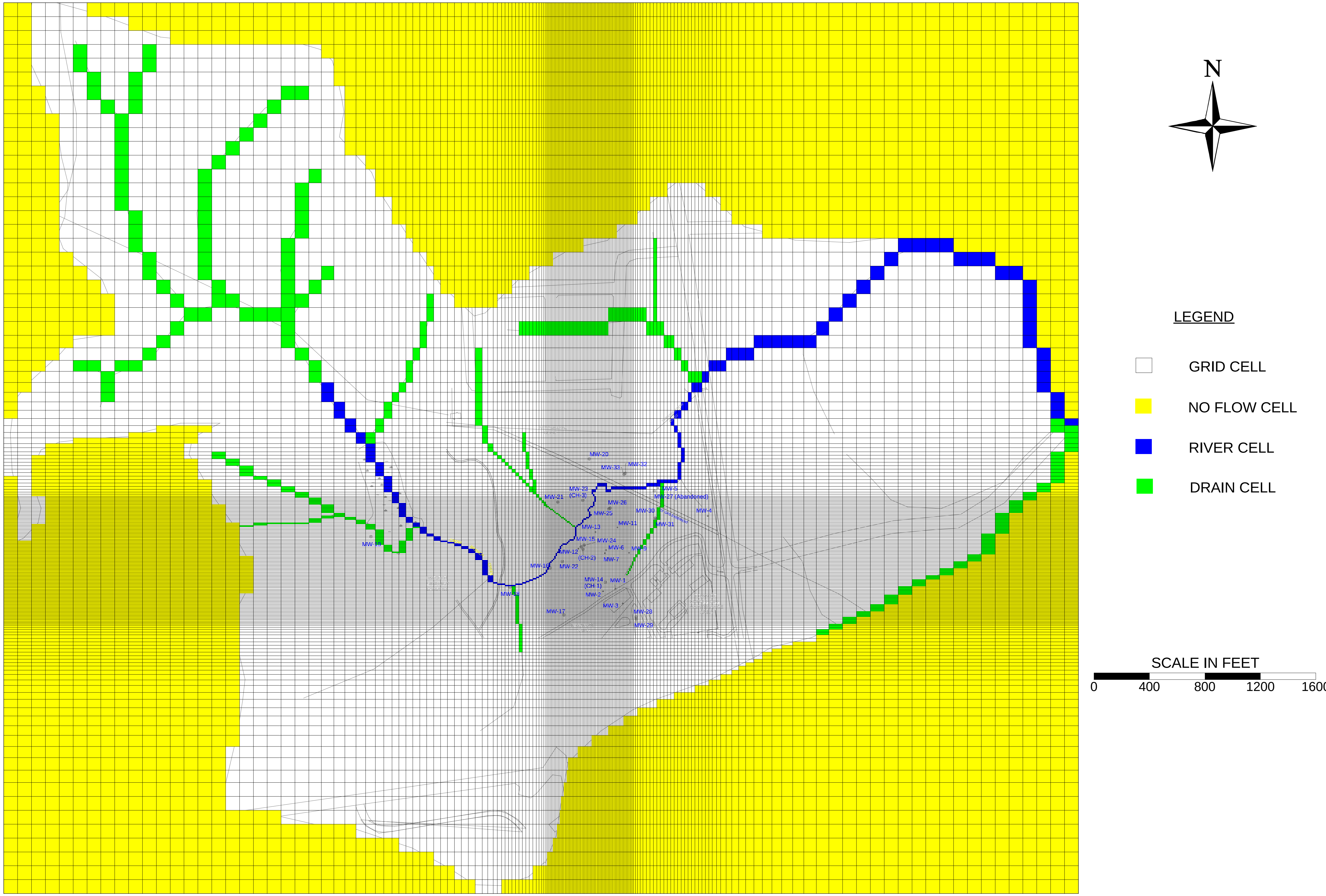
ARCADIS 1114 Benfield Boulevard, Suite A Millersville, Maryland 21108 Tel (410) 987-0032 Fax (410) 987-4392	SITE LOCATION MAP UNC AIRPORT ROAD WASTE DISPOSAL AREA CHAPEL HILL, NORTH CAROLINA	PROJECT MANAGER: MPK DRAFTER: JWR PROJECT NUMBER: NC000239.0013	DEPARTMENT MANAGER: PJS CHECKED: MPK DRAWING NUMBER: 1-1



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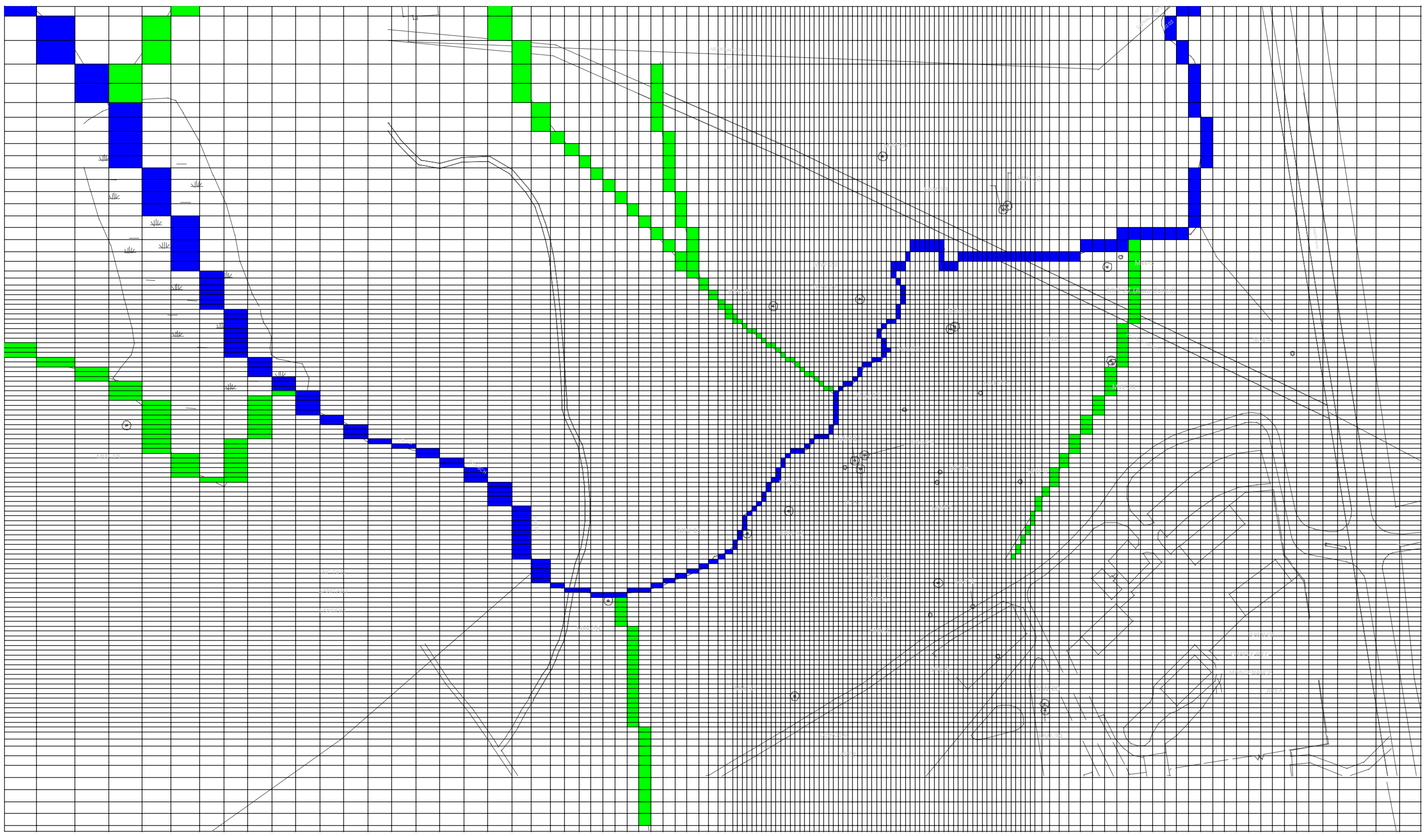
PROJECT NO.: NC000239.0013	
DRAWING: SURFER	
FILE NO: Fig 5_1 regional grid	
PLOT SIZE: 17" x 22"	
DRAFTED BY: JWR	DATE: 12/04
CHECKED BY: MPK	DATE: 12/04
APPROVED BY: MPK	DATE: 12/04

FULL MODEL GRID AND BOUNDARY CONDITIONS IN MODEL LAYER 1

UNC AIRPORT ROAD WASTE DISPOSAL AREA
CHAPEL HILL, NORTH CAROLINA

FIGURE

5-1



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LOCAL MODEL GRID AND BOUNDARY CONDITIONS IN MODEL LAYER 1

UNC AIRPORT ROAD WASTE DISPOSAL AREA
CHAPEL HILL, NORTH CAROLINA

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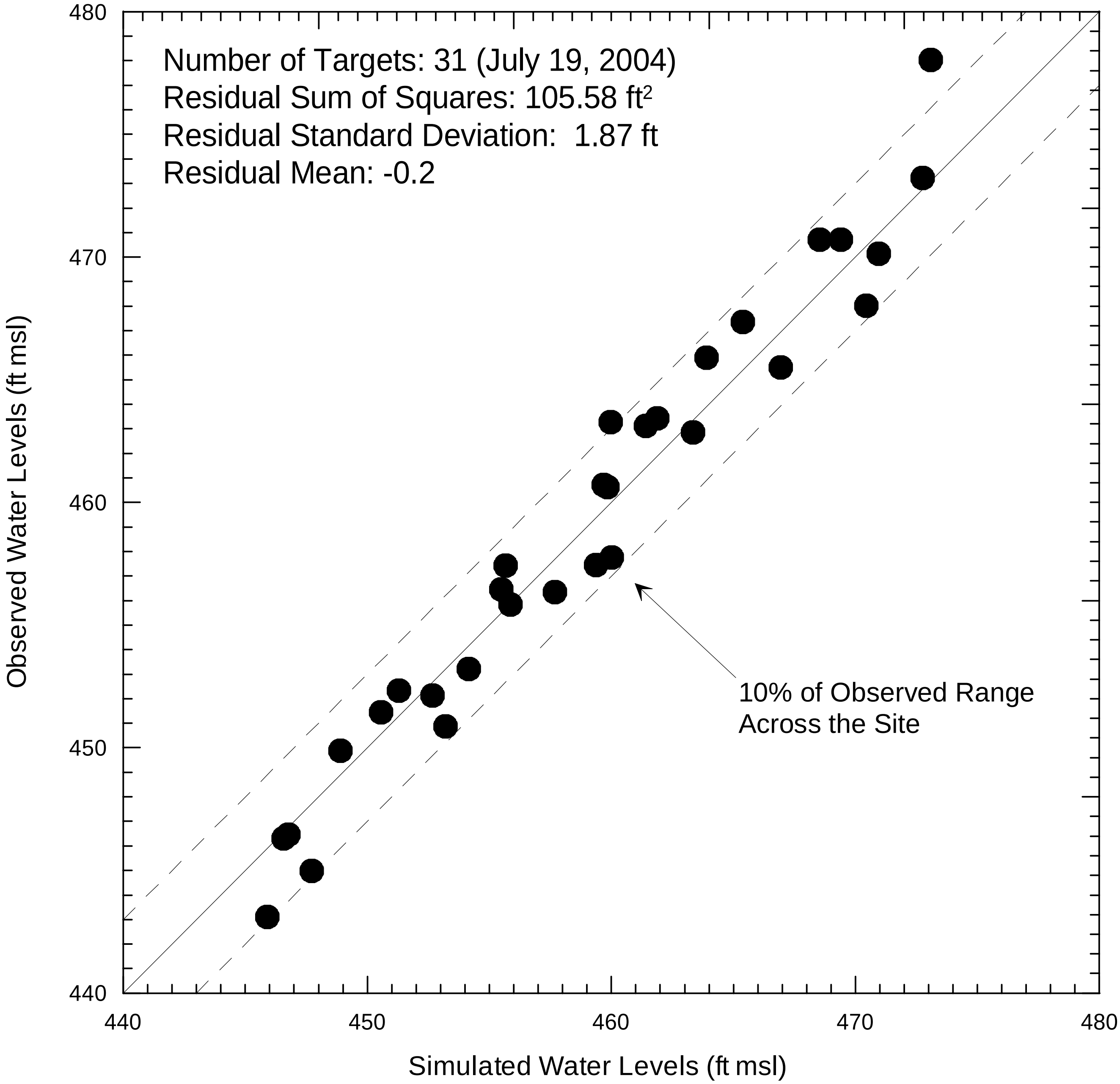

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FILE NO.: Grapher
PRJCT NO.: NC000239.0013
DWG DATE: 12/04

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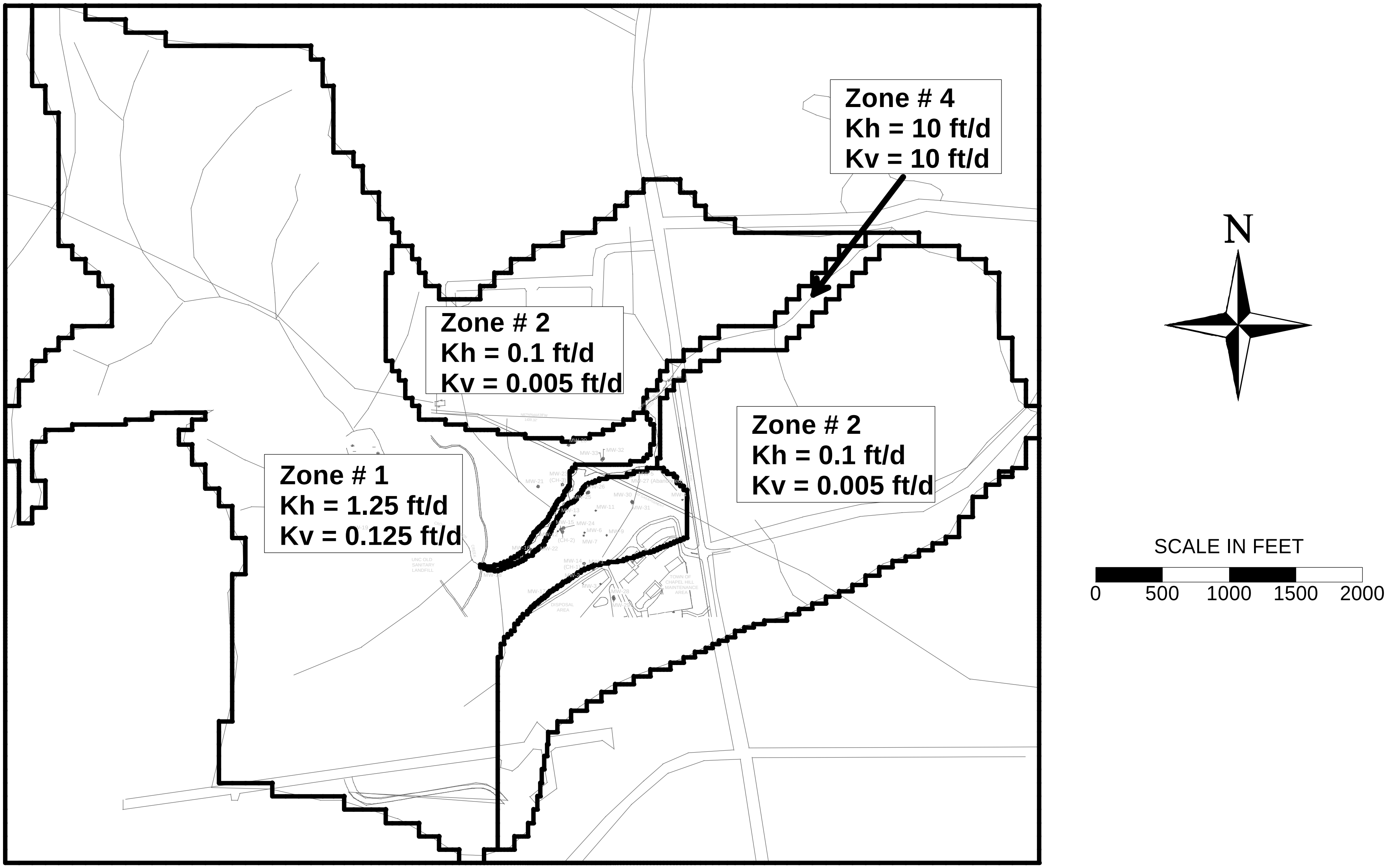
Observed Versus Simulated Water Levels
With Calibrated Statistics

UNC AIRPORT ROAD WASTE DISPOSAL AREA
CHAPEL HILL, NORTH CAROLINA

FIGURE
6- 1



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HYDRAULIC CONDUCTIVITY ZONES
IN MODEL LAYER 1

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CHAPEL HILL, NORTH CAROLINA

PROJECT MANAGER MPK	DEPARTMENT MANAGER PJS
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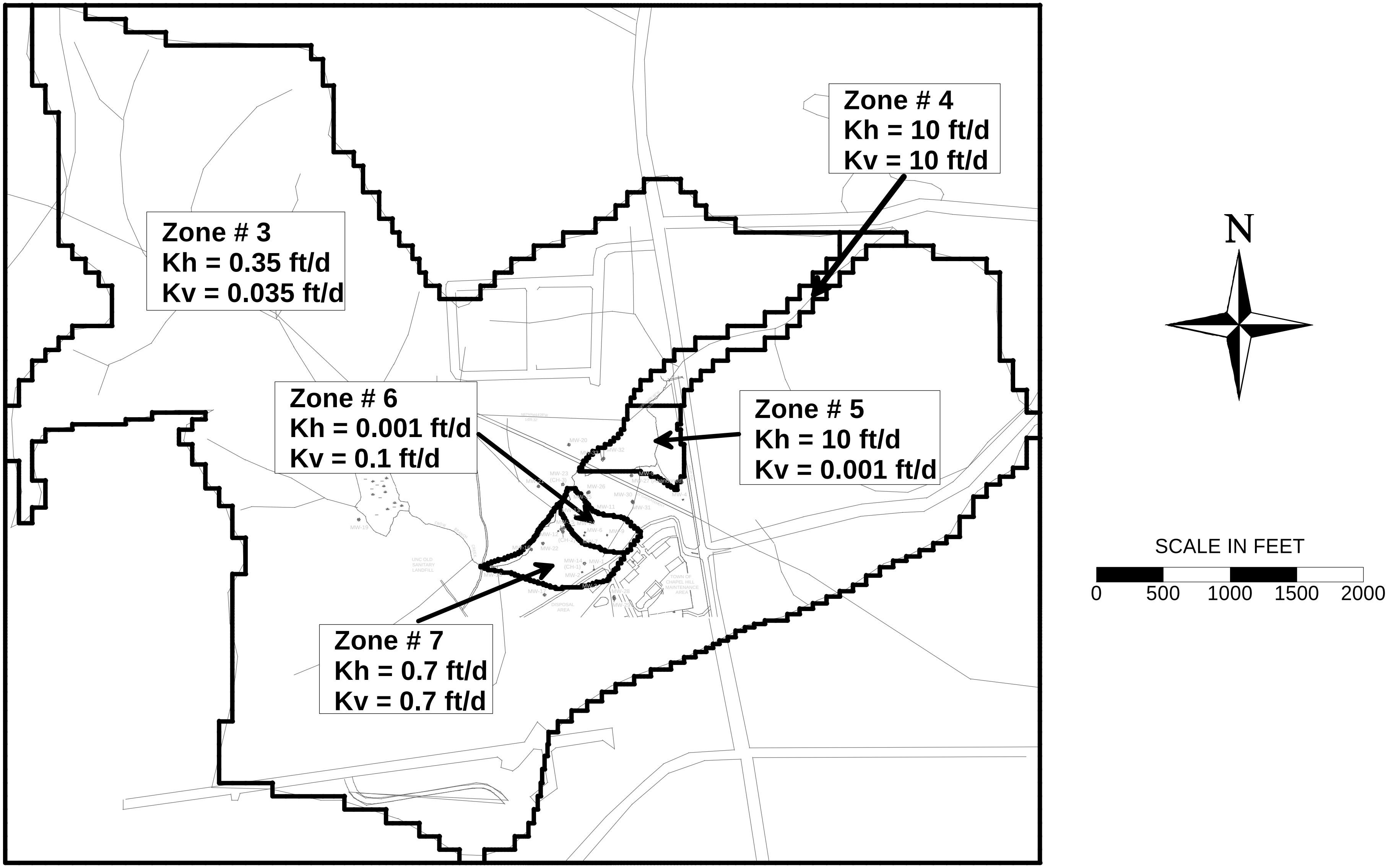
PROJECT NUMBER NC000239.0013	DRAWING NUMBER 6-2



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HYDRAULIC CONDUCTIVITY ZONES
IN MODEL LAYER 2

UNC AIRPORT ROAD WASTE DISPOSAL AREA
CHAPEL HILL, NORTH CAROLINA

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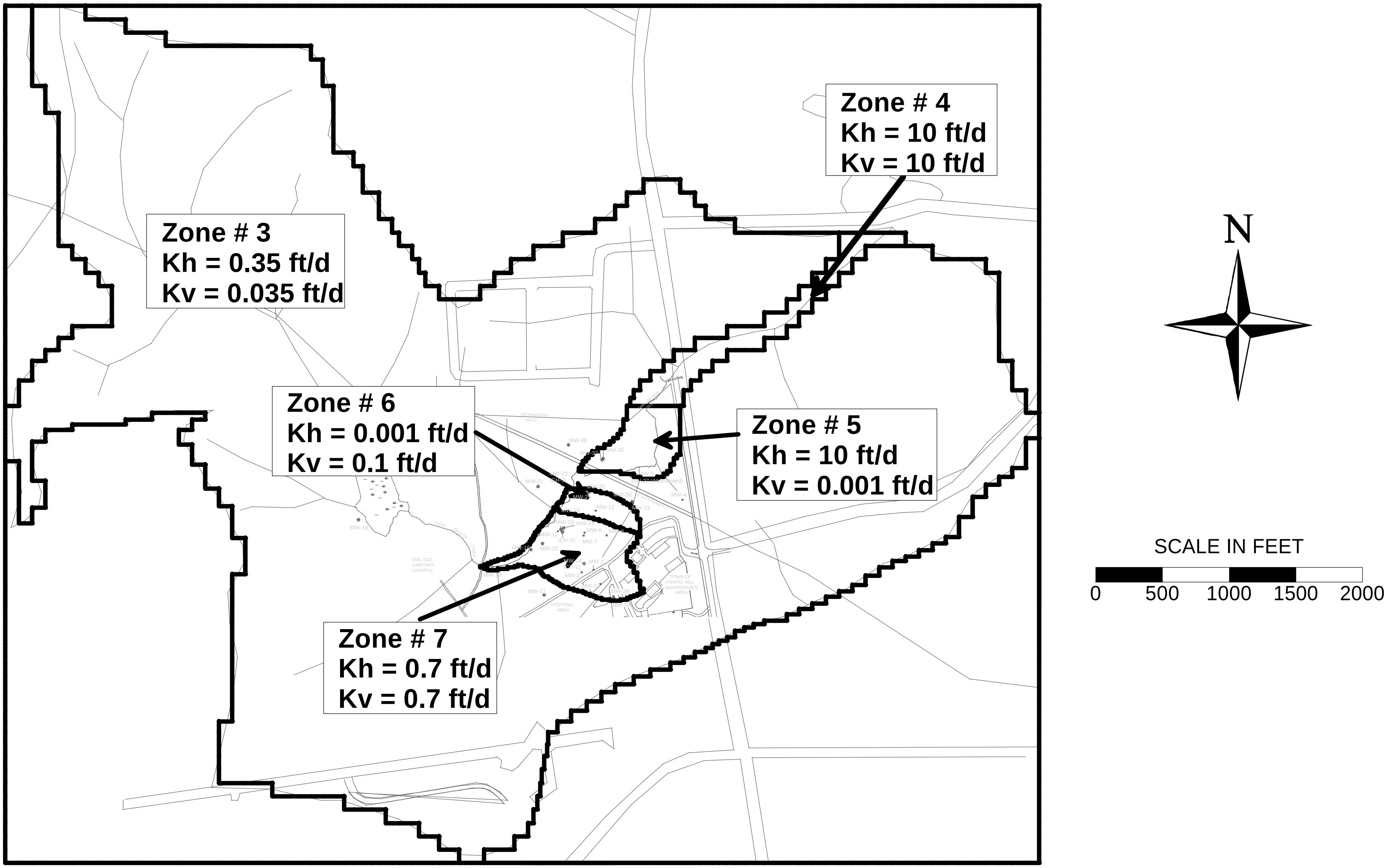

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HYDRAULIC CONDUCTIVITY ZONES
IN MODEL LAYER 3

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CHAPEL HILL, NORTH CAROLINA

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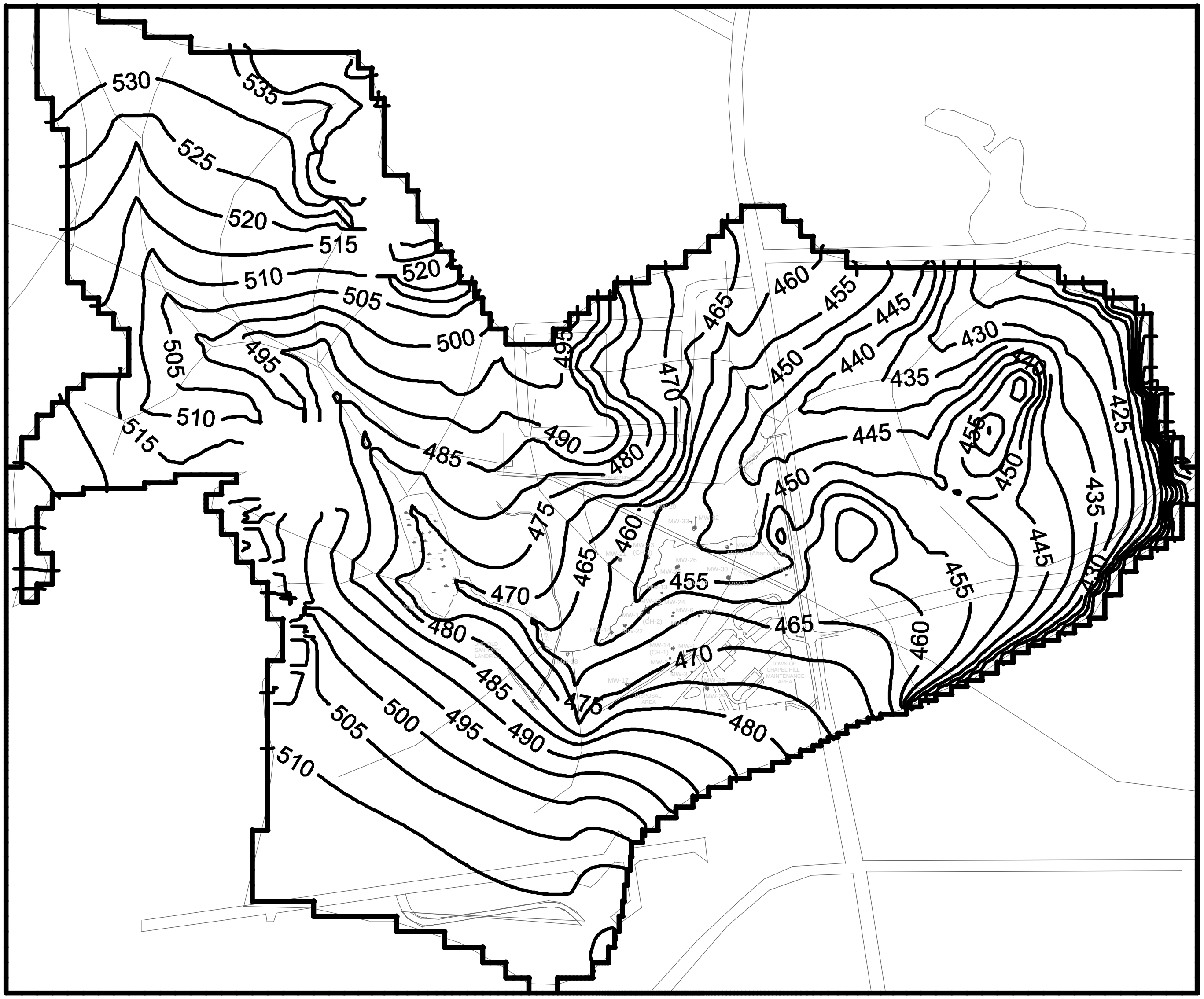

N

LEGEND

— 470 — Simulated Water Level (ft NGVD)

SCALE IN FEET

0 500 1000 1500 2000

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SIMULATED WATER LEVELS
IN MODEL LAYER 1

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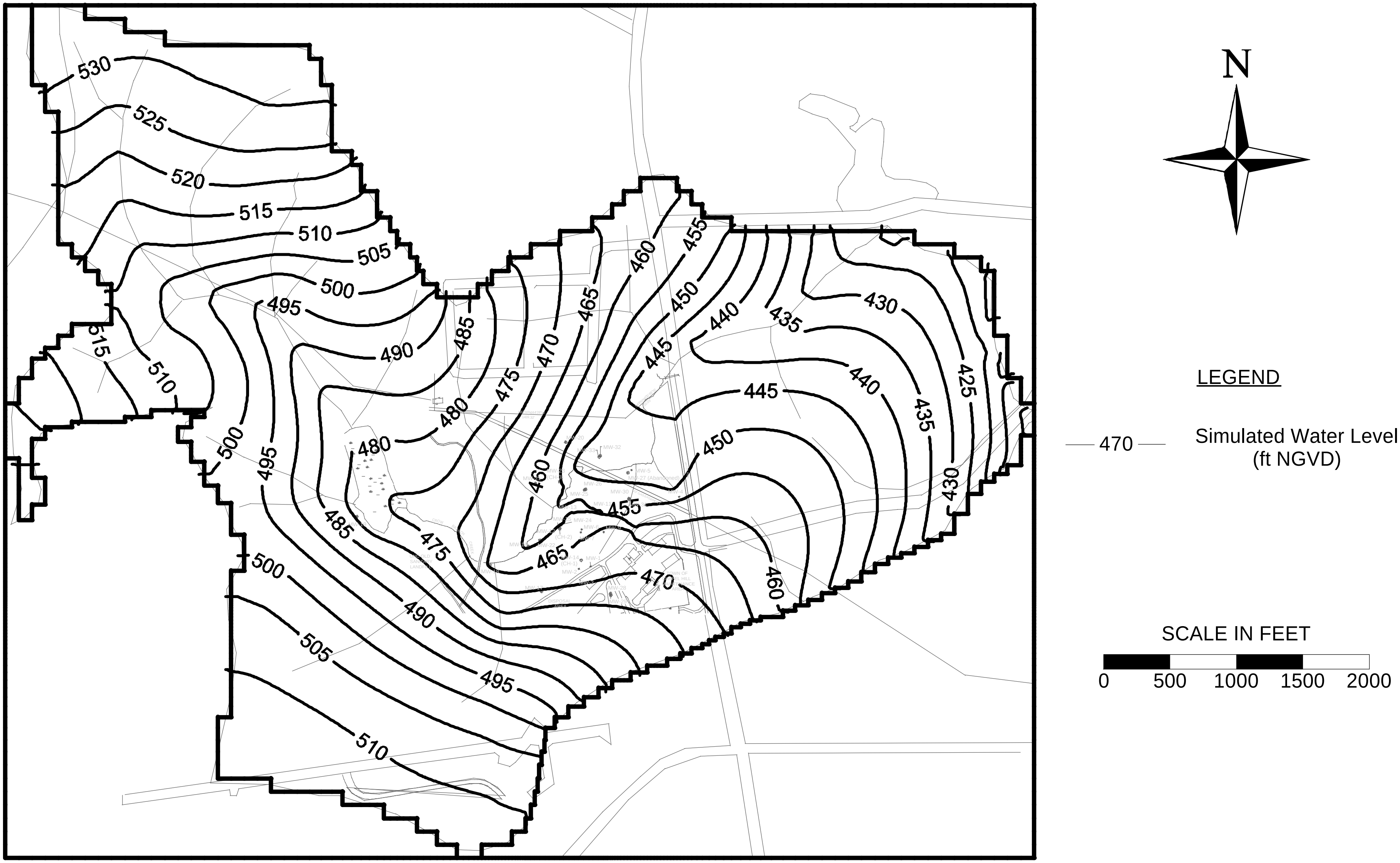
CHAPEL HILL, NORTH CAROLINA

PROJECT MANAGER MPK	DEPARTMENT MANAGER PJS
DRAWN JWR	CHECKED MPK
PROJECT NUMBER NC000239.0013	DRAWING NUMBER 6-5



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SIMULATED WATER LEVELS
IN MODEL LAYER 2

UNC AIRPORT ROAD WASTE DISPOSAL AREA
CHAPEL HILL, NORTH CAROLINA

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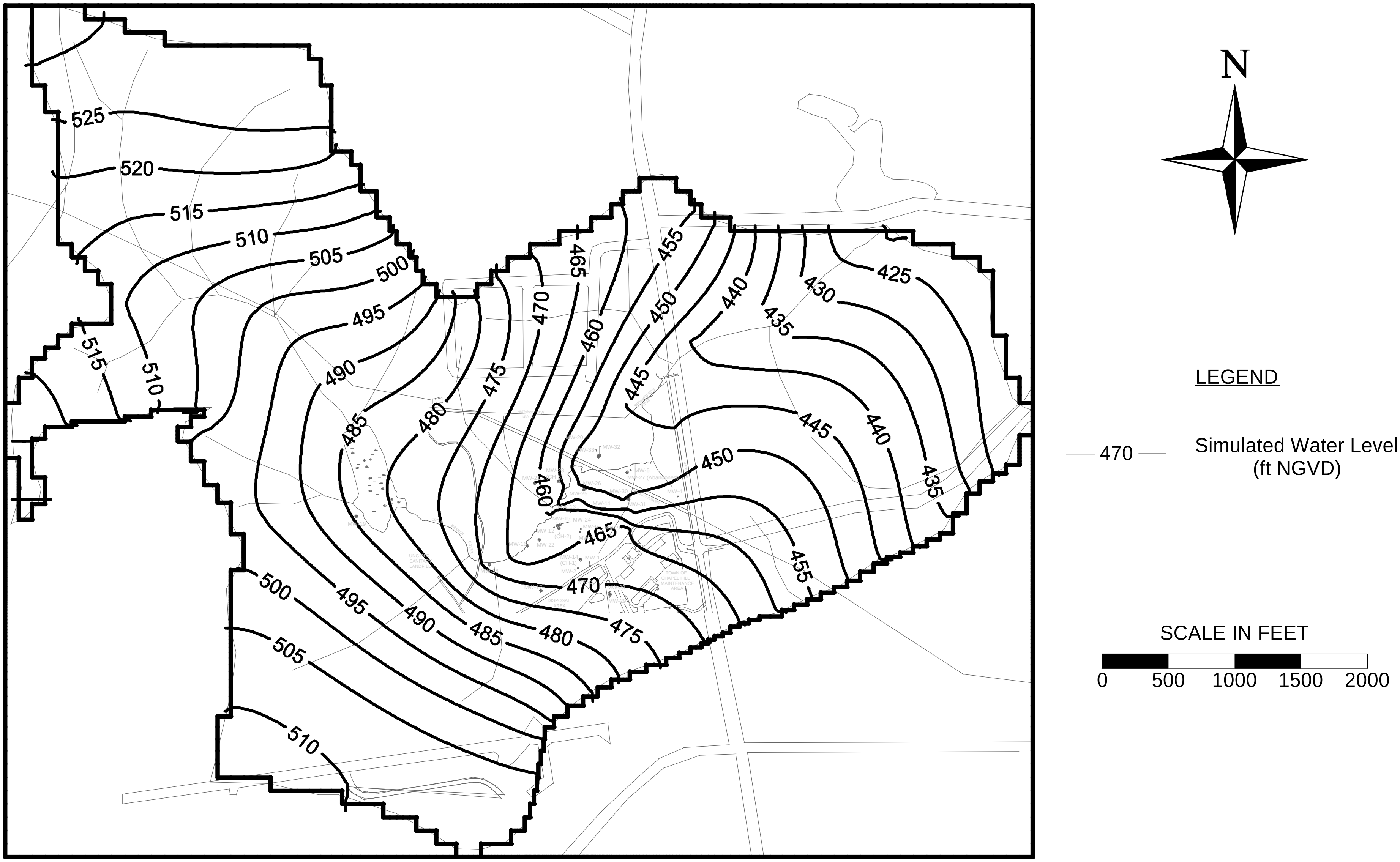
PROJECT NUMBER NC000239.0013	DRAWING NUMBER 6-6



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SIMULATED WATER LEVELS
IN MODEL LAYER 3

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CHAPEL HILL, NORTH CAROLINA

PROJECT MANAGER MPK	DEPARTMENT MANAGER PJS
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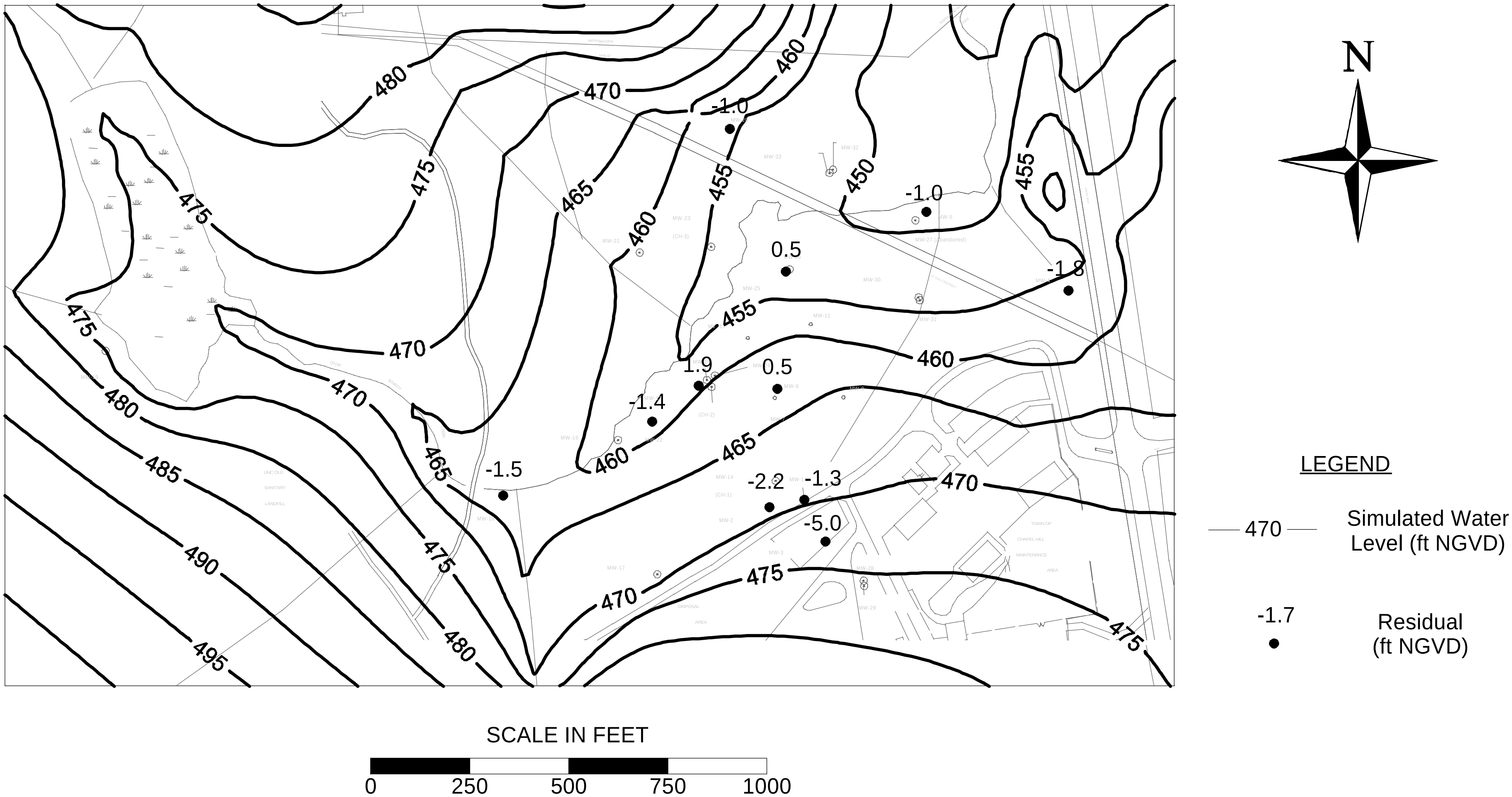

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SIMULATED WATER LEVELS ON THE SITE AND CALIBRATION RESIDUALS IN MODEL LAYER 1

UNC AIRPORT ROAD WASTE DISPOSAL AREA
CHAPEL HILL, NORTH CAROLINA

PROJECT MANAGER MPK	DEPARTMENT MANAGER PJS
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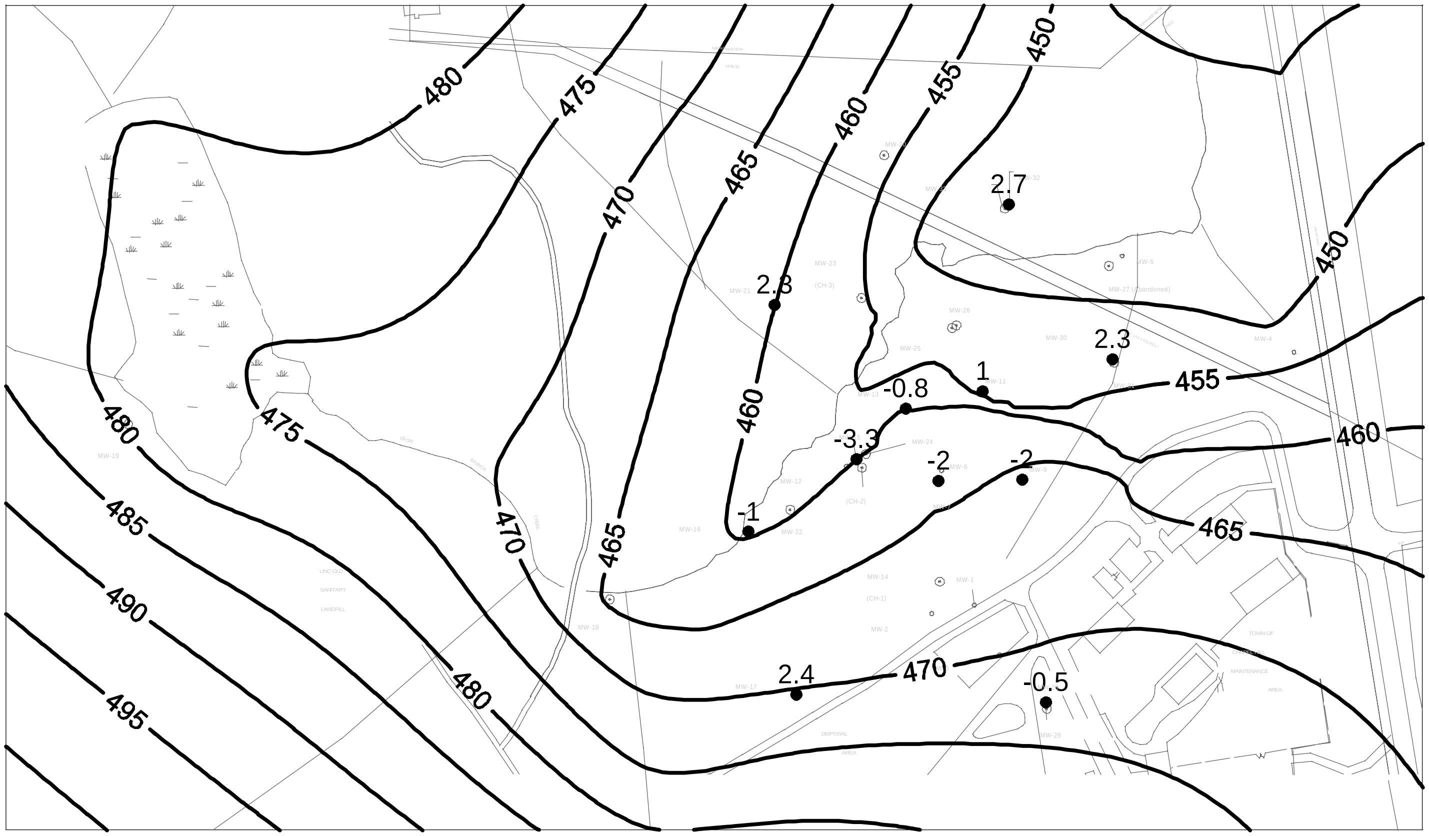
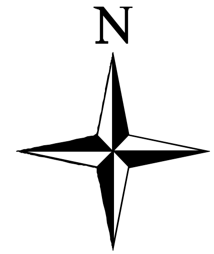
PROJECT NUMBER NC000239.0013	DRAWING NUMBER 6-8





LEGEND

470 — Simulated Water Level (ft NGVD)

-1.7 ● Residual (ft NGVD)

SCALE IN FEET

0 250 500 750 1000

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SIMULATED WATER LEVELS ON THE SITE AND CALIBRATION RESIDUALS IN MODEL LAYER 2

UNC AIRPORT ROAD WASTE DISPOSAL AREA
CHAPEL HILL, NORTH CAROLINA

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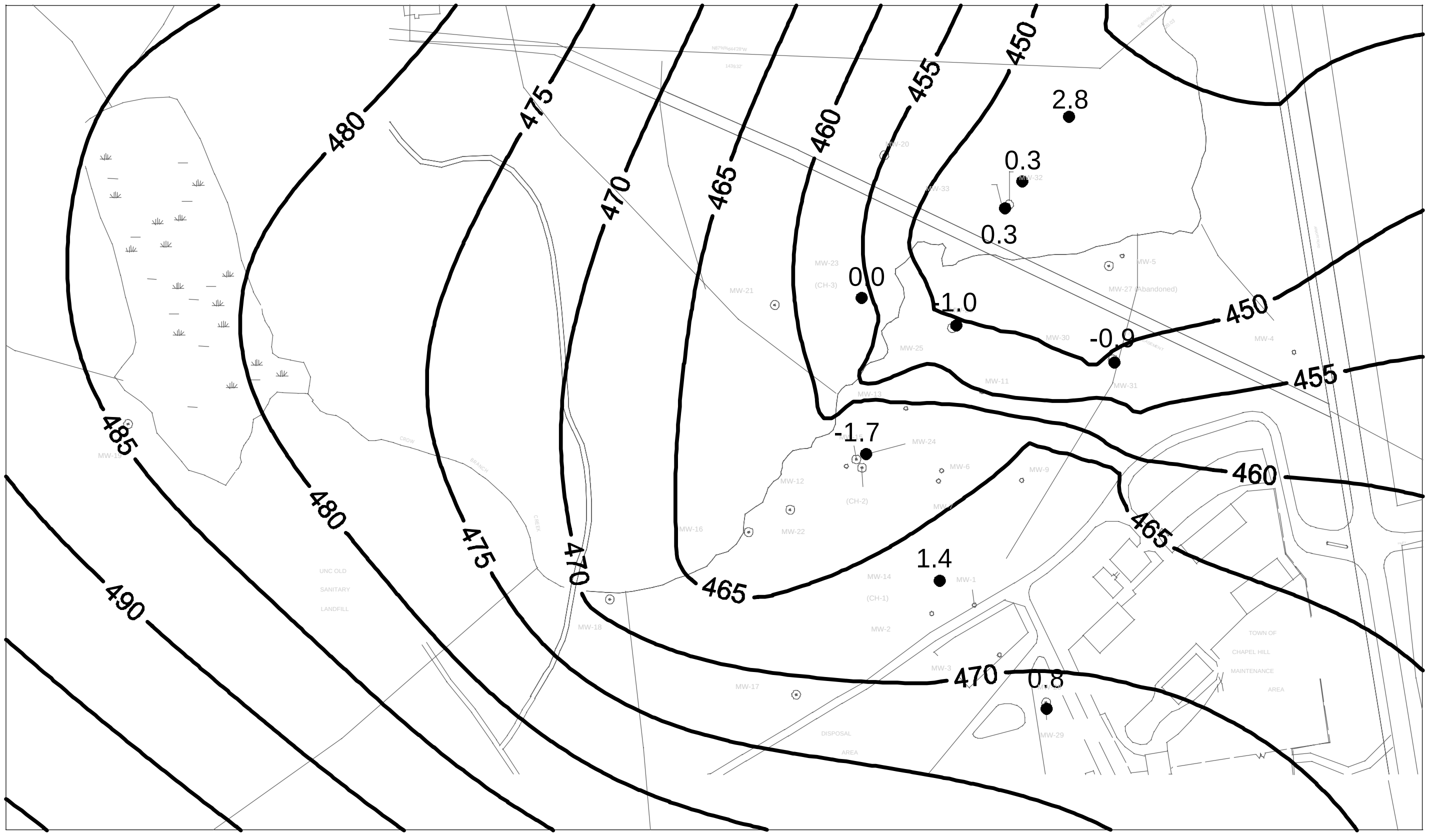
DRAWN: JWR	CHECKED: MPK
PROJECT NUMBER: NC000239.0013	DRAWING NUMBER: 6-9



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LEGEND

470 — Simulated Water Level (ft NGVD)

-1.7 ● Residual (ft NGVD)

SCALE IN FEET

0 250 500 750 1000

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SIMULATED WATER LEVELS ON THE SITE AND CALIBRATION RESIDUALS IN MODEL LAYER 3

UNC AIRPORT ROAD WASTE DISPOSAL AREA
CHAPEL HILL, NORTH CAROLINA

PROJECT MANAGER MPK	DEPARTMENT MANAGER PJS
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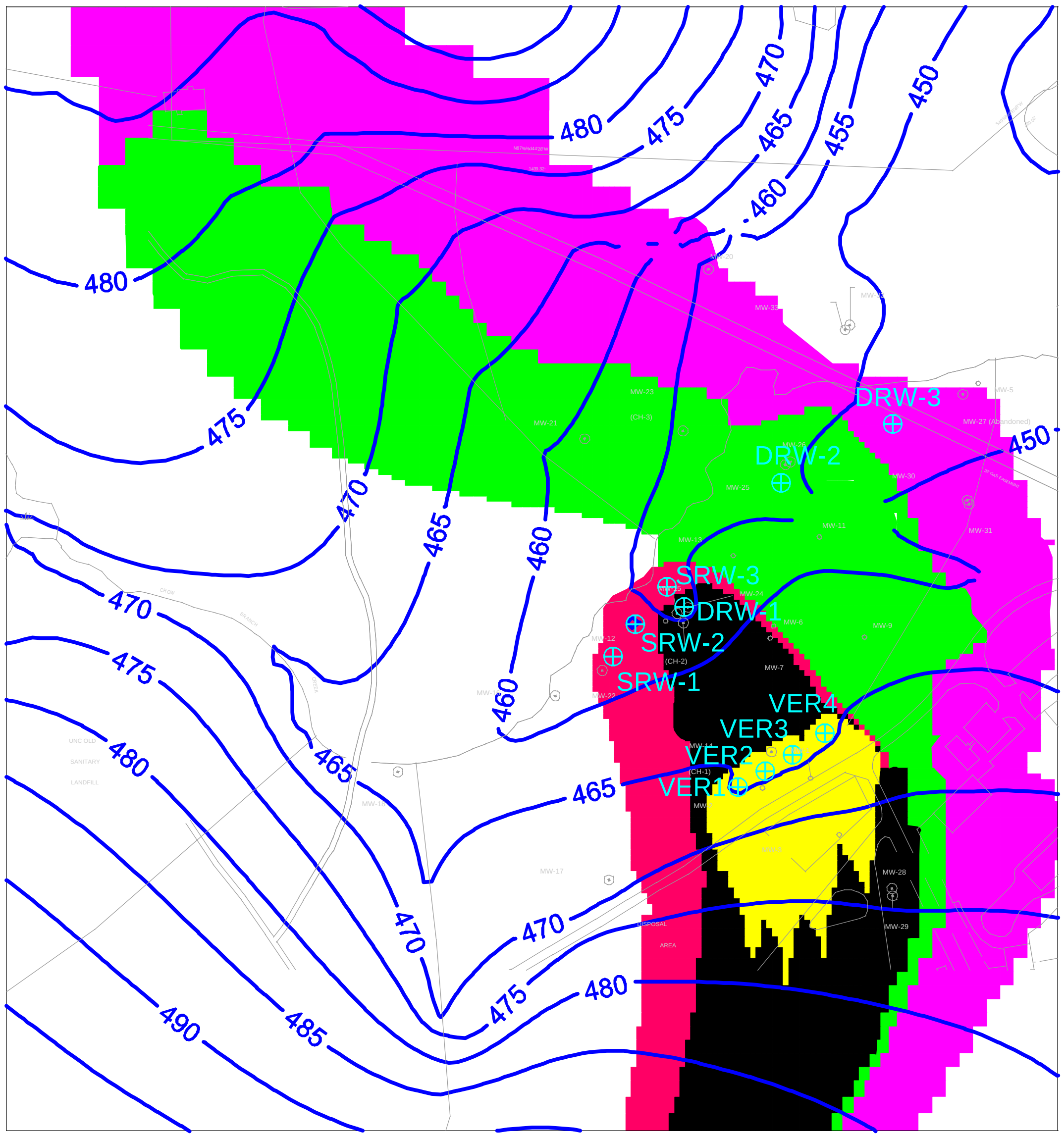

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CAPTURE ZONE	WELL IDs	WITHDRAWAL RATE (gpm)
(red)	SRW1, SRW2, SRW3	2.2 (Total)
(yellow)	VER1, VER2, VER3, VER4	0.8 (Total)
(magenta)	DRW3	10.0
(green)	DRW2	3.0
(black)	DRW1	5.0
		Total = 21 gpm

470 Simulated Water Level (ft NGVD)

⊕ Well

SCALE IN FEET

0 250 500 750 1000

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SIMULATED WATER LEVELS AND RECOVERY WELL CAPTURE ZONES IN MODEL LAYER 1

UNC AIRPORT ROAD WASTE DISPOSAL AREA
CHAPEL HILL, NORTH CAROLINA

PROJECT MANAGER MPK	DEPARTMENT MANAGER PJS
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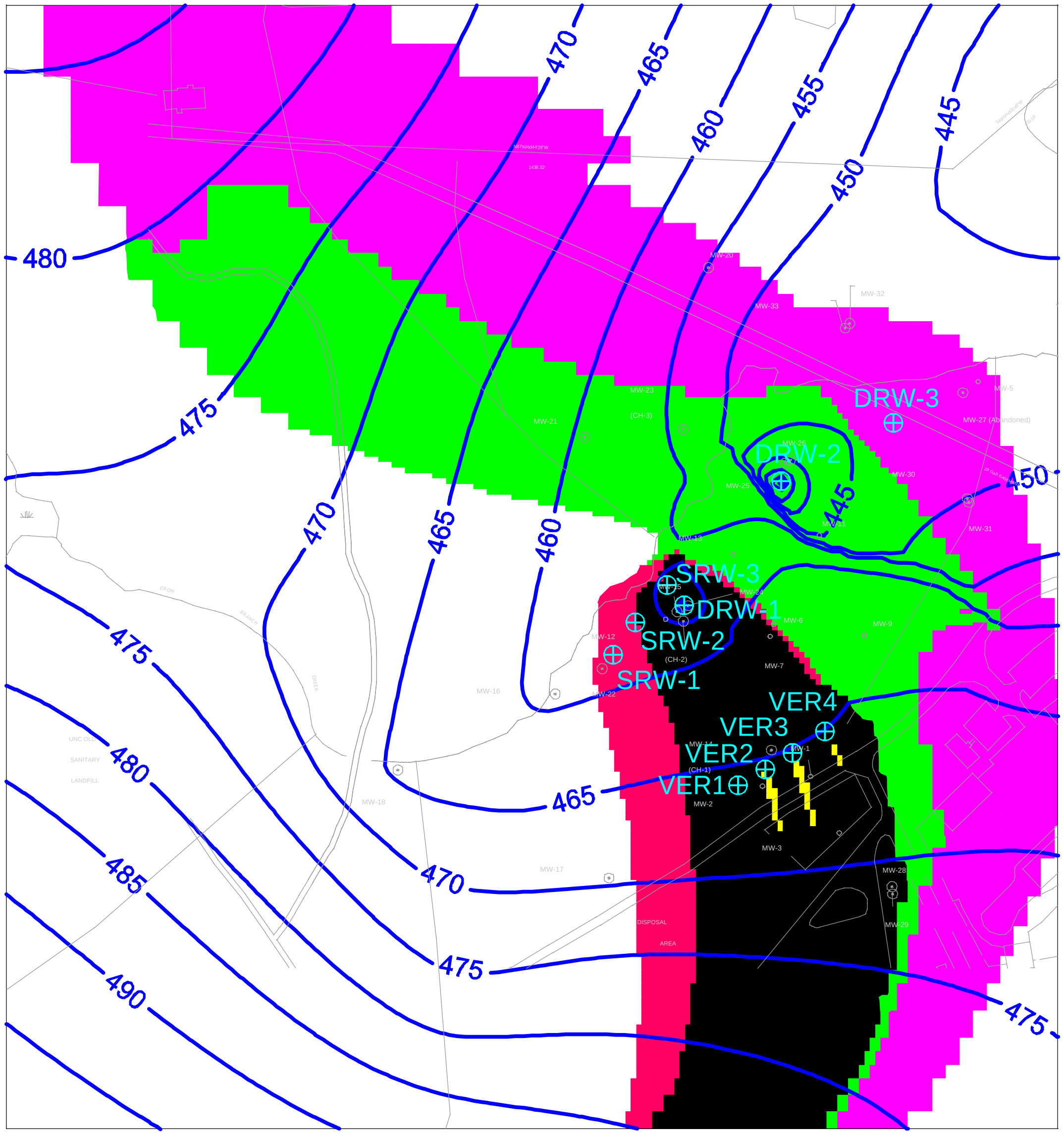
PROJECT NUMBER NC000239.0013	DRAWING NUMBER 7-1



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LEGEND

CAPTURE ZONE	WELL IDs	WITHDRAWAL RATE (gpm)
	SRW1, SRW2, SRW3	2.2 (Total)
	VER1, VER2, VER3, VER4	0.8 (Total)
	DRW3	10.0
	DRW2	3.0
	DRW1	5.0
		Total = 21 gpm

—470— Simulated Water Level (ft NGVD)

⊕ Well

SCALE IN FEET

0 250 500 750 1000

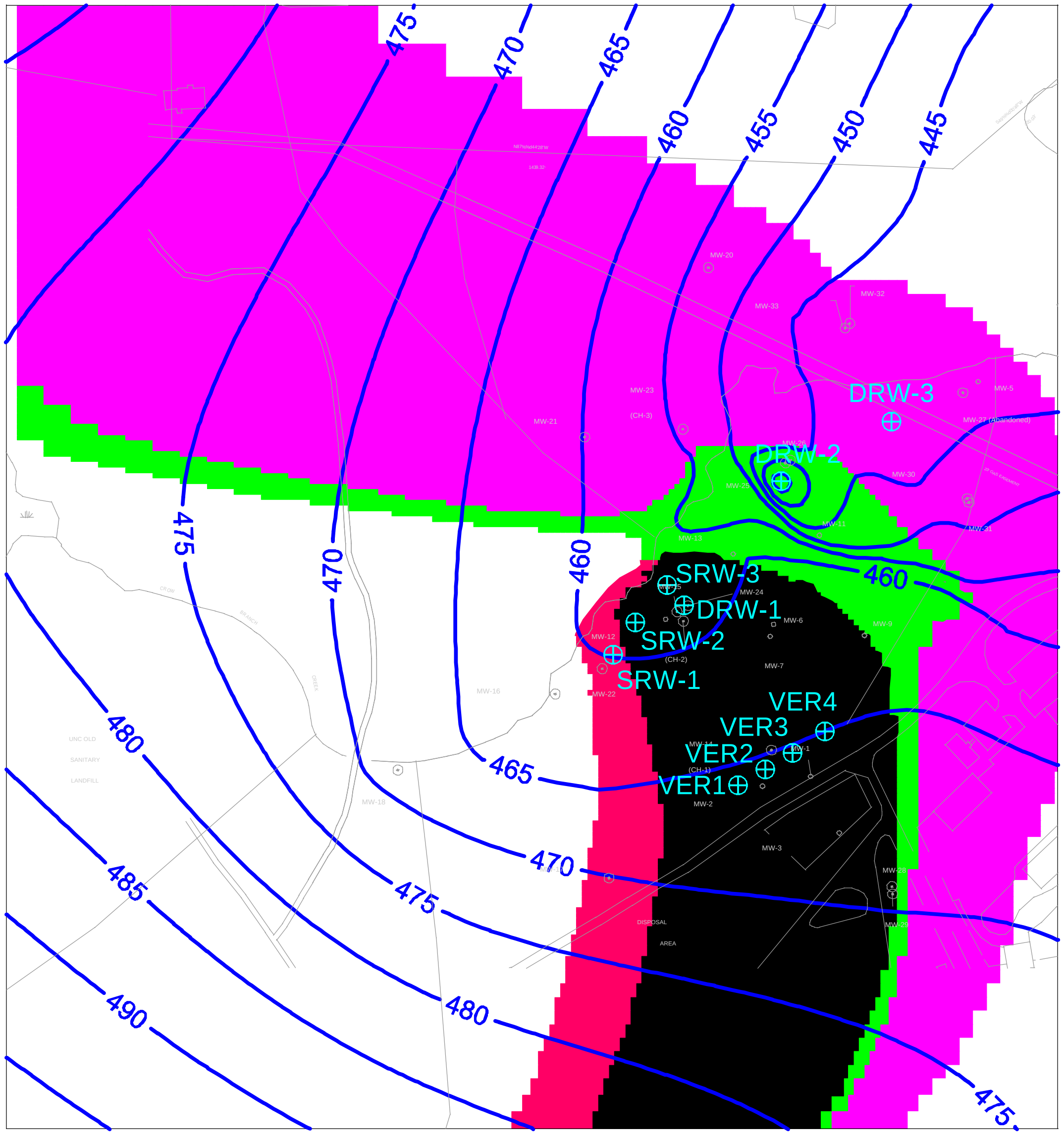
ARCADIS

1114 Benfield Boulevard, Suite A
Millersville, Maryland 21108
Tel (410) 987-0032 Fax (410) 987-4392

SIMULATED WATER LEVELS AND RECOVERY WELL CAPTURE ZONES IN MODEL LAYER 2

UNC AIRPORT ROAD WASTE DISPOSAL AREA
CHAPEL HILL, NORTH CAROLINA

PROJECT MANAGER MPK	DEPARTMENT MANAGER PJS
DRAWN JWR	CHECKED MPK
PROJECT NUMBER NC000239.0013	DRAWING NUMBER 7-2



N

LEGEND

CAPTURE ZONE	WELL IDs	WITHDRAWAL RATE (gpm)
(red)	SRW1, SRW2, SRW3	2.2 (Total)
(yellow)	VER1, VER2, VER3, VER4	0.8 (Total)
(magenta)	DRW3	10.0
(green)	DRW2	3.0
(black)	DRW1	5.0
		Total = 21 gpm

470 Simulated Water Level (ft NGVD)

⊕ Well

SCALE IN FEET

0 250 500 750 1000

ARCADIS

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Millersville, Maryland 21108
Tel (410) 987-0032 Fax (410) 987-4392

SIMULATED WATER LEVELS AND RECOVERY WELL CAPTURE ZONES IN MODEL LAYER 3

UNC AIRPORT ROAD WASTE DISPOSAL AREA
CHAPEL HILL, NORTH CAROLINA

PROJECT MANAGER MPK	DEPARTMENT MANAGER PJS
DRAWN JWR	CHECKED MPK
PROJECT NUMBER NC000239.0013	DRAWING NUMBER 7-3

Tables

Table 2-1. Estimated aquifer parameters from the DRW-1 pumping test, UNC Airport Road Waste Disposal Area, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

Observation Well	Saturated Thickness (ft)	Solution Equation	Hydraulic Conductivity (ft/d)	Storage Coefficient
DRW-1	80	Unconfined Theis	0.1655	0.4042
DRW-1	80	Moench Slab Fracture	0.1589	0.1234**
OW-5	80	Unconfined Theis	0.1296	0.0004632
OW-6	80	Unconfined Theis	0.1354	0.000399
MW-7	80	Unconfined Theis	0.1381	0.0001195
MW-12	80	Unconfined Theis	0.2344	0.002428
MW-14	154.8	Unconfined Theis	0.1399	0.00001109
MW-15	80	Unconfined Theis	0.1315	0.0004472
AVERAGE*			0.153629	0.058295

* Calculated from the primary storativity (0.001542/ft) and the aquifer thickness (80 ft).

** Does not include the Moench Slab Fracture analysis of DRW-1 data.

Table 2-2. Estimated aquifer parameters from the VER-1 pumping test, UNC Airport Road Waste Disposal Area, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

Observation Well	Hydraulic Conductivity (ft/d)	
	Unconfined Theis	Moench Spherical Fracture
MW-1	1.307	0.597
MW-2	2.367	0.118[1]
OW-A	1.570	1.598
OW-B	1.995	1.880
OW-C	1.791	1.921
OW-D	2.957	2.923
AVERAGE	1.998	1.506

[1] From a manual calibration; all other values in this table were estimated automatically.

Table 6-1. Calibration residuals from the groundwater flow model. UNC Airport Road Waste Disposal Area, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

WELL	OBSERVED HEAD July 19, 2004 (ft msl)	CALCULATED HEAD (ft msl)	RESIDUAL (ft)
MW-1	470.71	469.42	-1.29
MW-2	470.70	468.53	-2.17
MW-3	478.04	473.08	-4.96
MW-4	457.43	455.66	-1.77
MW-5	449.87	448.89	-0.98
MW-6	462.85	463.34	0.49
MW-7	465.91	463.89	-2.02
MW-9	467.35	465.38	-1.97
MW-11	453.21	454.16	0.95
MW-12	457.44	459.38	1.94
MW-13	460.62	459.85	-0.77
MW-14	465.50	466.94	1.44
MW-15	463.27	459.98	-3.29
MW-16	460.72	459.67	-1.05
MW-17	468.02	470.45	2.43
MW-18	463.42	461.89	-1.53
MW-20	456.45	455.49	-0.96
MW-21	457.76	460.02	2.26
MW-22	456.34	457.69	1.35
MW-23	455.83	455.87	0.04
MW-24	463.12	461.42	-1.70
MW-25	452.14	452.68	0.54
MW-26	452.34	451.29	-1.05
MW-28	473.22	472.76	-0.46
MW-29	470.13	470.97	0.84
MW-30	450.87	453.21	2.34
MW-31	451.45	450.56	-0.90
MW-32	444.99	447.73	2.74
MW-33	446.46	446.77	0.31
MW-34est	443.11	445.91	2.80
MW-37est	446.31	446.562	0.252

Table 6-2. Flow model input parameter values. UNC Airport Road Waste Disposal Area, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

Parameter	Units	Zone	Value	
Recharge	in/year		7.00	
Hydraulic Conductivity	ft/d		**Horizontal (Kh)**	**Vertical (Kv)**
		1	1.25	0.125
		2	0.10	0.005
		3	0.35	0.035
		4	10.00	10.00
		5	10.00	0.001
		6	0.001	0.10
		7	0.70	0.70

Table 6-3. Sensitivity analysis for the groundwater flow model. UNC Airport Road Waste Disposal Area, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

Parameter	Zone	Multiplied by 0.8		Multiplied by 1.2	
		RSS[1]	Mean Res.[2]	RSS[1]	Mean Res.[2]
Hydraulic Conductivity	1	99.31	-0.12	115.82	0.45
	2	96.50	-0.04	121.91	0.39
	3	102.26	0.15	106.91	0.23
	4	106.88	0.05	103.90	0.30
	5	104.22	0.19	105.05	0.20
	6	101.59	0.02	112.98	0.34
	7	108.89	0.06	103.06	0.29
Leakance	1	100.73	0.14	108.15	0.24
	2	103.48	0.17	105.78	0.22
	3	96.80	0.13	111.21	0.25
	4	101.75	0.09	107.58	0.28
	5	104.82	0.20	104.59	0.19
	6	101.47	0.12	107.47	0.25
	7	104.65	0.19	104.65	0.19
Recharge		228.32	1.46	129.68	-1.02

[1] The calibrated model RSS was 104.65

[2] The calibrated model mean residual was 0.1938

Table 7-1. Shallow recovery wells in the remedial design. UNC Airport Road Waste Disposal Area, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

Well ID	Model Grid (Figure 5-1)			Simulated flow rate (gpm)	Approximate Depth (ft bgs)
	Layer	Row	Column		
VER[1]-1	1	121	98	0.2	25
VER-2	1	118	103	0.2	25
VER-3	1	115	108	0.2	25
VER-4	1	111	114	0.2	25
SRW[2]-1	1	85	84	0.6	15
SRW-2	1	92	78	0.6	15
SRW-3	1	98	74	1.0	15

[1] Vaccuum-enhanced recovery well.
[2] Shallow recovery well.

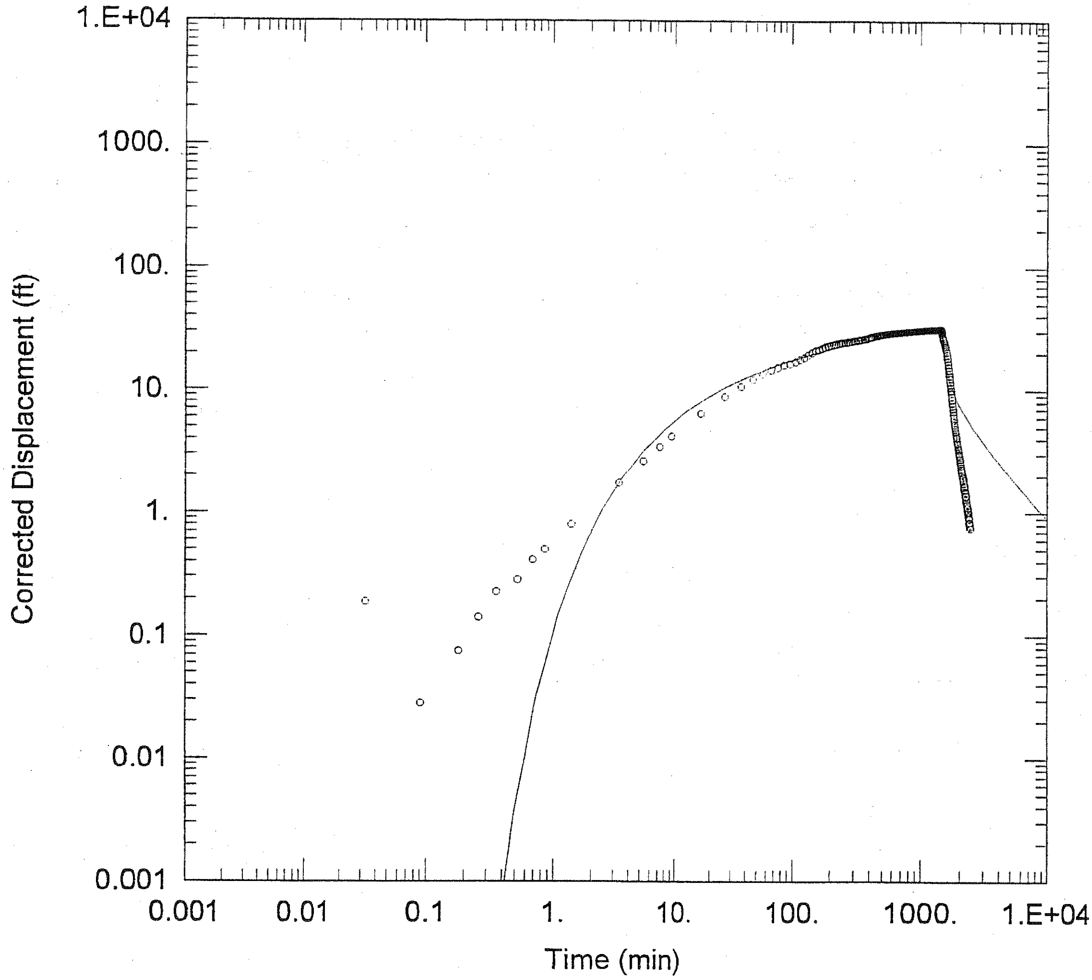
Table 7-2. Deep conventional recovery wells in the remedial design. UNC Airport Road Waste Disposal Area, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

Well ID	Model Grid (Figure 5-1)			Design flow rate (gpm)	Approximate Depth (ft bgs)
	Layers	Row	Column		
DRW[1]-1	2	88	88	5.0	80
DRW-2	2	65	106	3.0	80
DRW-3	2 & 3	50	127	10.0	150

[1]Deep revovery well

Appendix A

AQTESOLV output for the DRW-1 pumping test



WELL TEST ANALYSIS

Data Set: D:\UNC\RW1TEST\RW1THIN.AQT
Date: 06/19/98 Time: 19:43:33

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: RW-1
Test Date: 05/06/98

AQUIFER DATA

Saturated Thickness: 80. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
RW-1	0	0

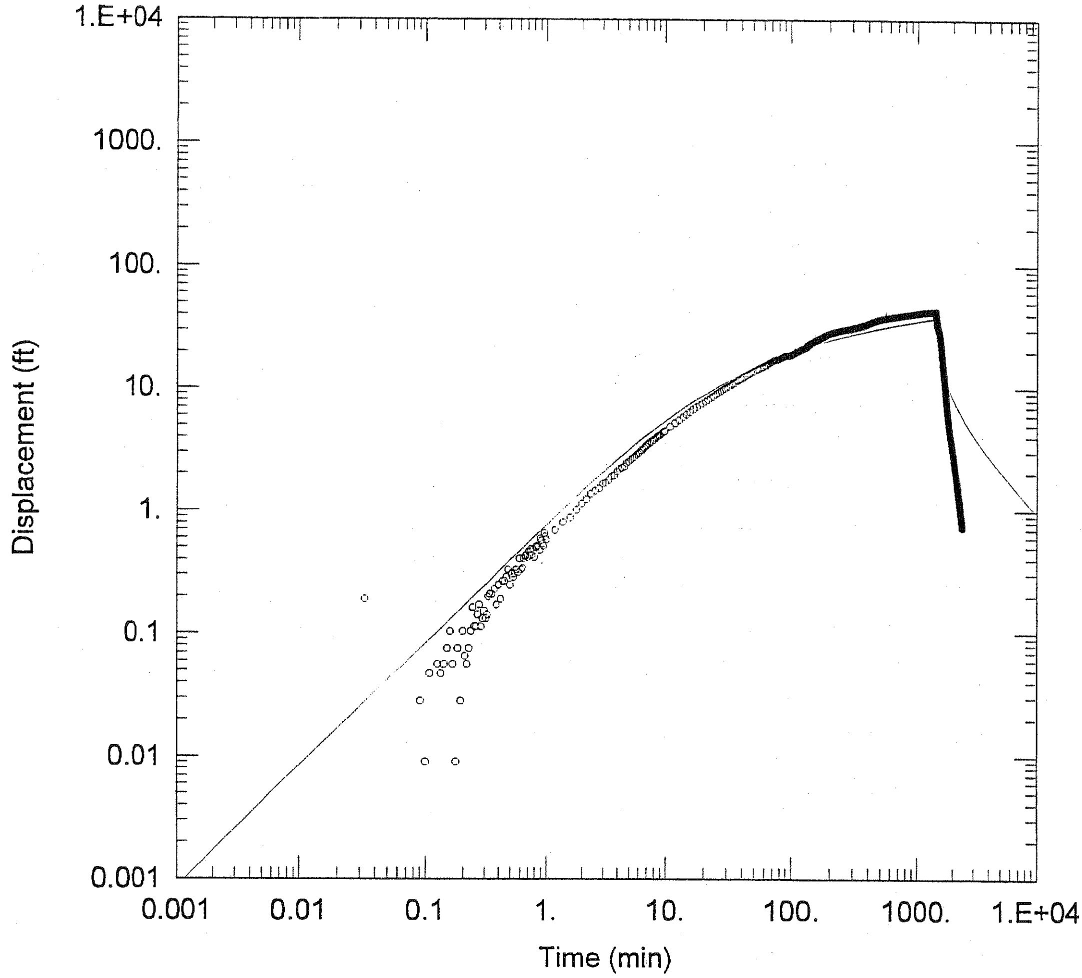
Observation Wells

Well Name	X (ft)	Y (ft)
◦ RW-1	0	0

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 13.32 ft^2/day
S = 0.4042



WELL TEST ANALYSIS

Data Set: D:\UNC\RW1TEST\RW1.AQT
Date: 06/19/98 Time: 19:32:46

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: RW-1
Test Date: 05/06/98

AQUIFER DATA

Saturated Thickness: 80. ft Slab Block Thickness: 5. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
RW-1	0	0

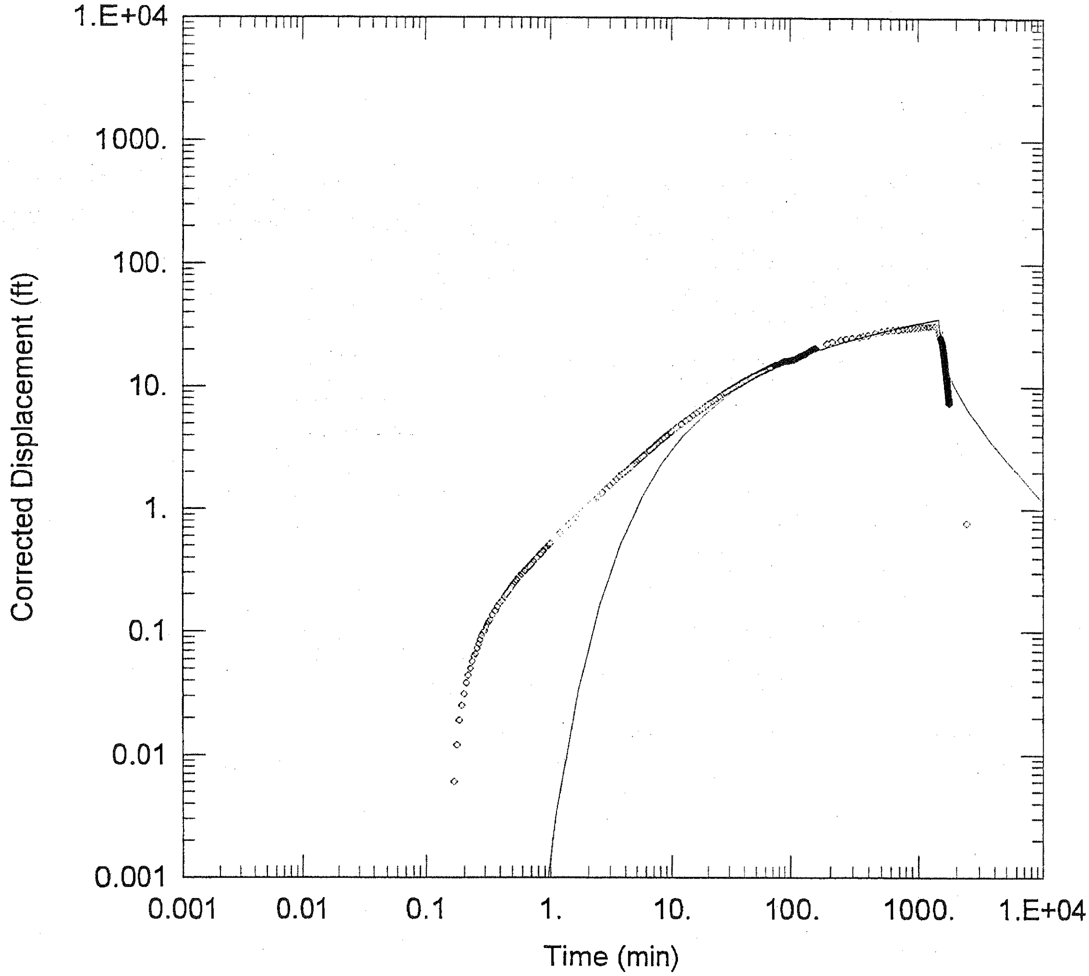
Observation Wells

Well Name	X (ft)	Y (ft)
◦ RW-1	0	0

SOLUTION

Aquifer Model: Fractured
Solution Method: Moench w/slab blocks

K = 0.1589 ft/day
Ss = 0.001542 ft^{-1}
K' = 1.44 ft/day
Ss' = 0.001 ft^{-1}



WELL TEST ANALYSIS

Data Set: D:\UNC\RW1TEST\OW5.AQT
Date: 06/19/98 Time: 19:33:34

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: RW-1
Test Date: 05/06/98

AQUIFER DATA

Saturated Thickness: 80. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
RW-1	0	0

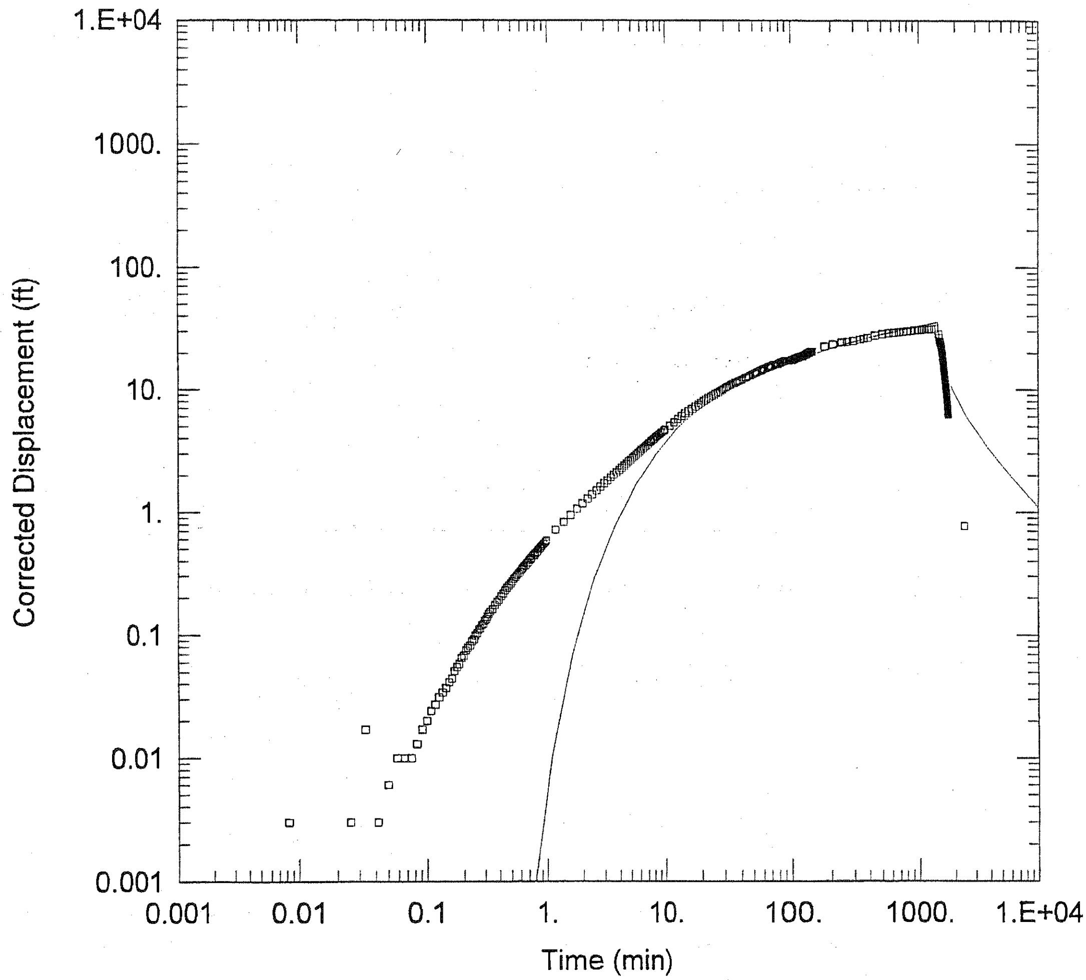
Observation Wells

Well Name	X (ft)	Y (ft)
OW 5	-20	0

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 10.37 ft^2/day
S = 0.0004632



WELL TEST ANALYSIS

Data Set: D:\UNC\RW1TEST\OW6.AQT
Date: 06/19/98 Time: 19:43:57

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: RW-1
Test Date: 05/06/98

AQUIFER DATA

Saturated Thickness: 80. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
RW-1	0	0

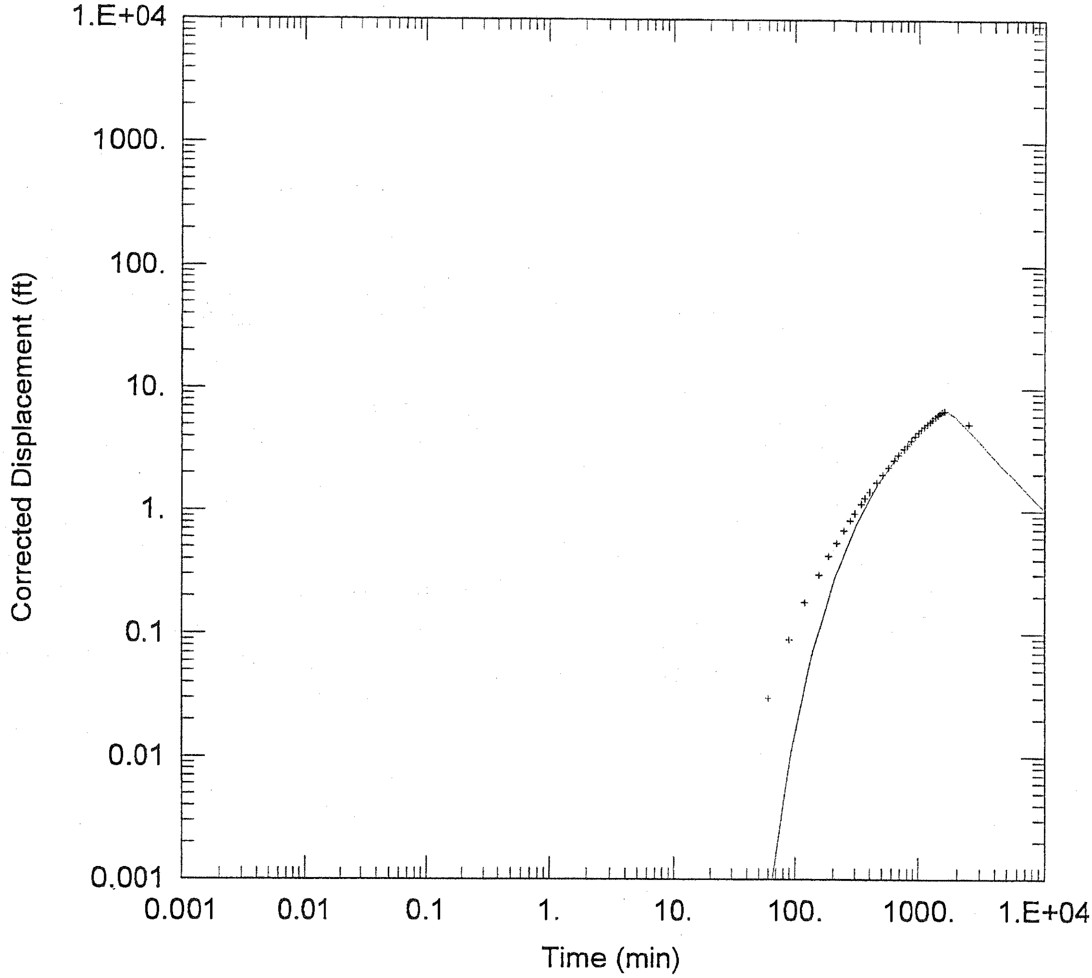
Observation Wells

Well Name	X (ft)	Y (ft)
▫ OW 6	0	-20

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 10.83 ft^2/day
S = 0.000399



WELL TEST ANALYSIS

Data Set: D:\UNC\RW1TEST\MW7.AQT
Date: 06/19/98 Time: 19:35:24

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: RW-1
Test Date: 05/06/98

AQUIFER DATA

Saturated Thickness: 80. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
RW-1	0	0

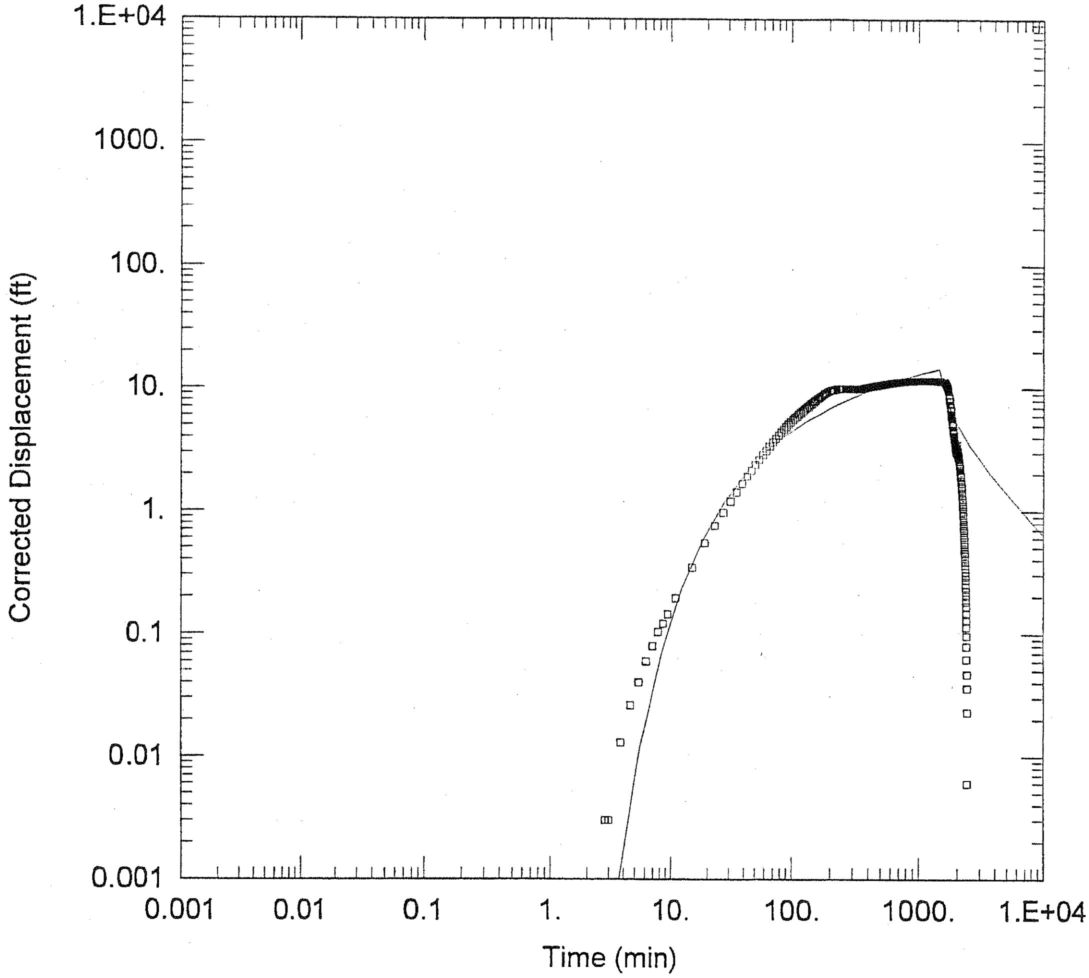
Observation Wells

Well Name	X (ft)	Y (ft)
+ MW-7	247.5	-227.5

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 11.05 ft^2/day
S = 0.0001195



WELL TEST ANALYSIS

Data Set: D:\UNC\RW1TEST\MW12.AQT
Date: 06/19/98 Time: 19:38:37

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: RW-1
Test Date: 05/06/98

AQUIFER DATA

Saturated Thickness: 80. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

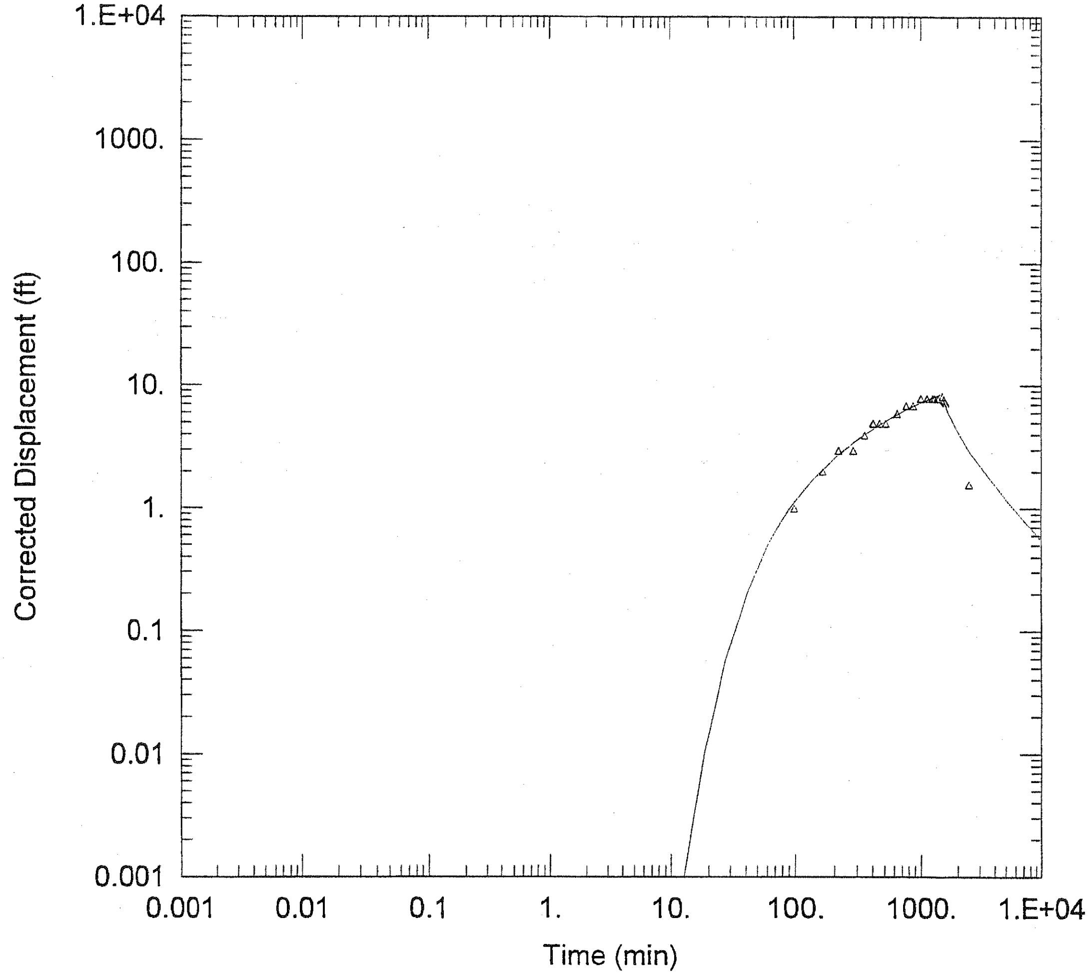
Well Name	X (ft)	Y (ft)
RW-1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ MW-12	-10	20

SOLUTION

Aquifer Model: Unconfined T = 18.75 ft^2/day
Solution Method: Theis S = 0.002428



WELL TEST ANALYSIS

Data Set: D:\UNC\RW1TEST\MW14.AQT
Date: 06/19/98 Time: 19:39:05

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: RW-1
Test Date: 05/06/98

AQUIFER DATA

Saturated Thickness: 154.8 ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
RW-1	0	0

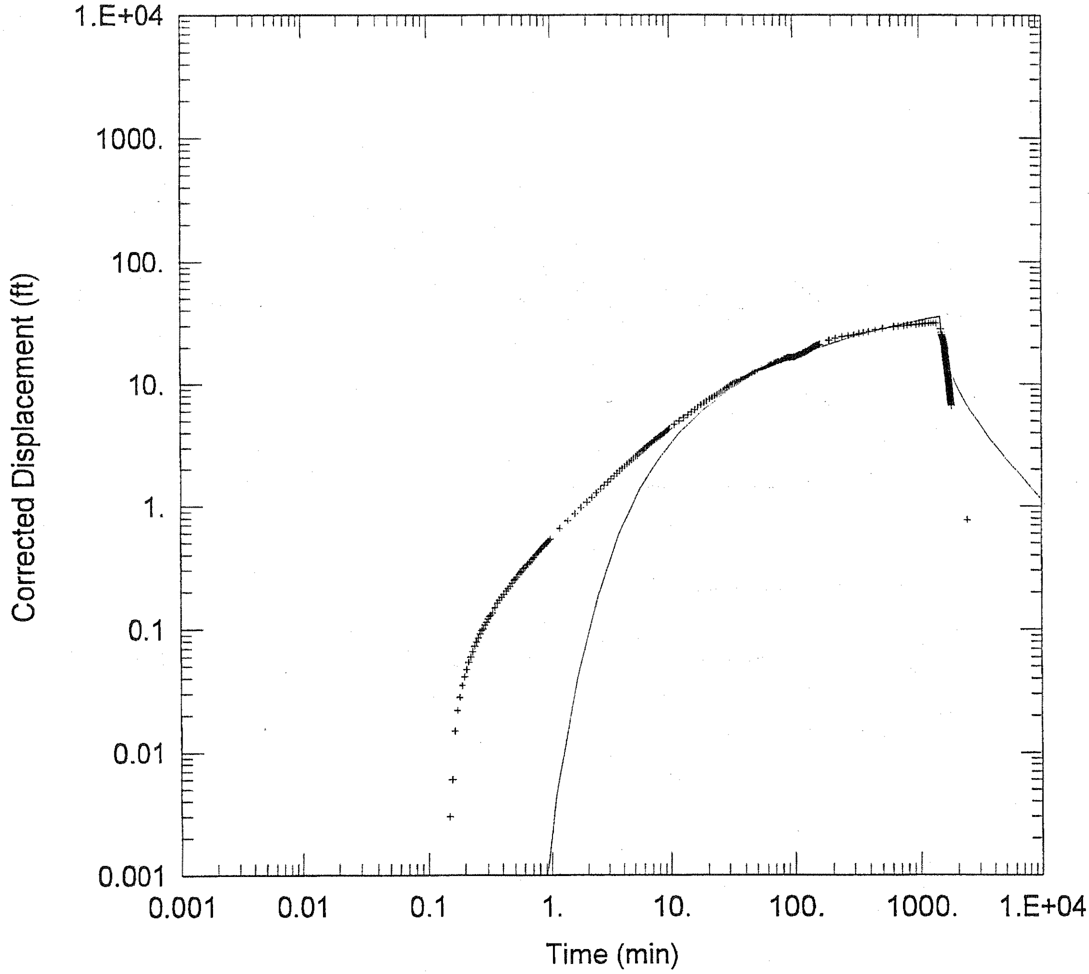
Observation Wells

Well Name	X (ft)	Y (ft)
△ MW14	0	-652

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 21.66 ft^2/day
S = 1.109E-05



WELL TEST ANALYSIS

Data Set: D:\UNC\RW1TEST\MW15.AQT
Date: 06/19/98 Time: 19:39:32

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: RW-1
Test Date: 05/06/98

AQUIFER DATA

Saturated Thickness: 80. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
RW-1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
+ MW-15	0	20

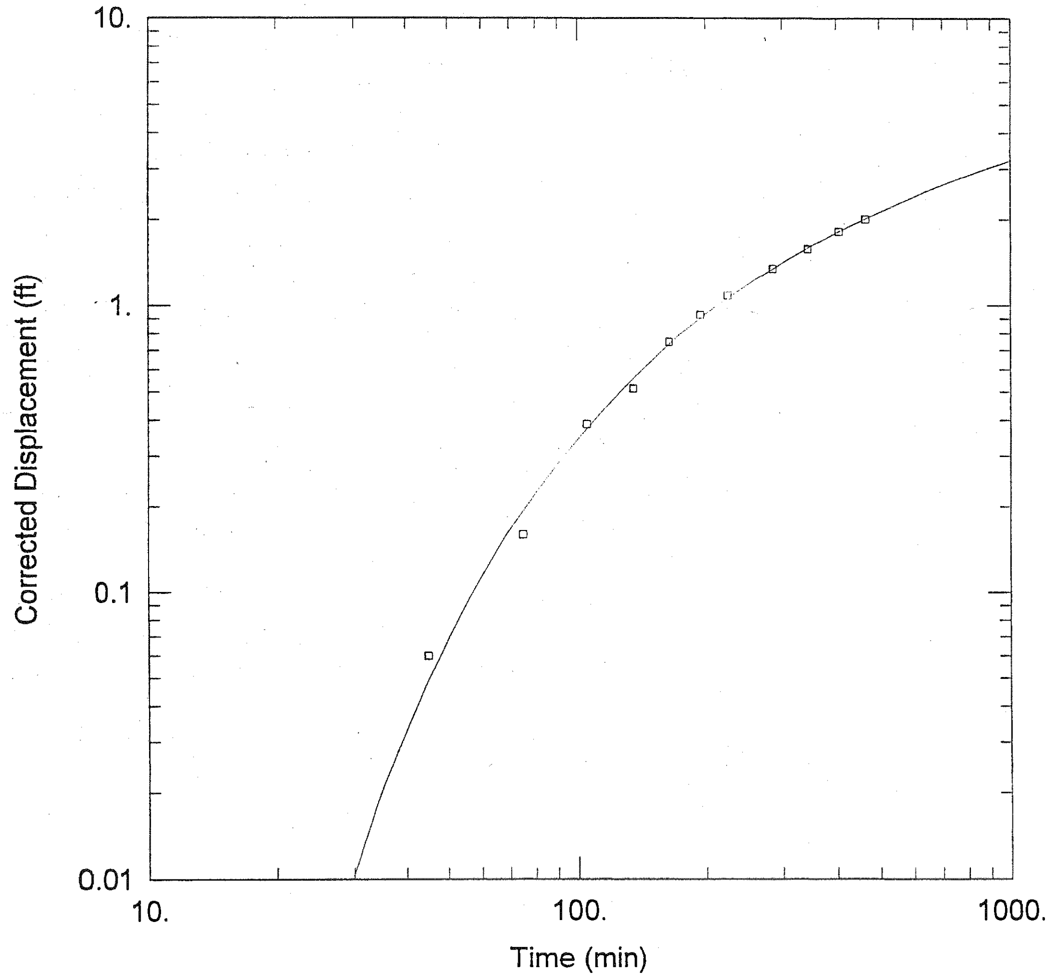
SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 10.52 ft^2/day
S = 0.0004472

Appendix B

AQTESOLV output for the VER-1 vacuum enhanced recovery test



WELL TEST ANALYSIS

Data Set: D:\UNC\PUMPTEST\VER1TEST\MW1.AQT
Date: 06/25/98 Time: 17:40:09

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: VER-1
Test Date: 4-30-98

AQUIFER DATA

Saturated Thickness: 20.91 ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
VER-1	0	0

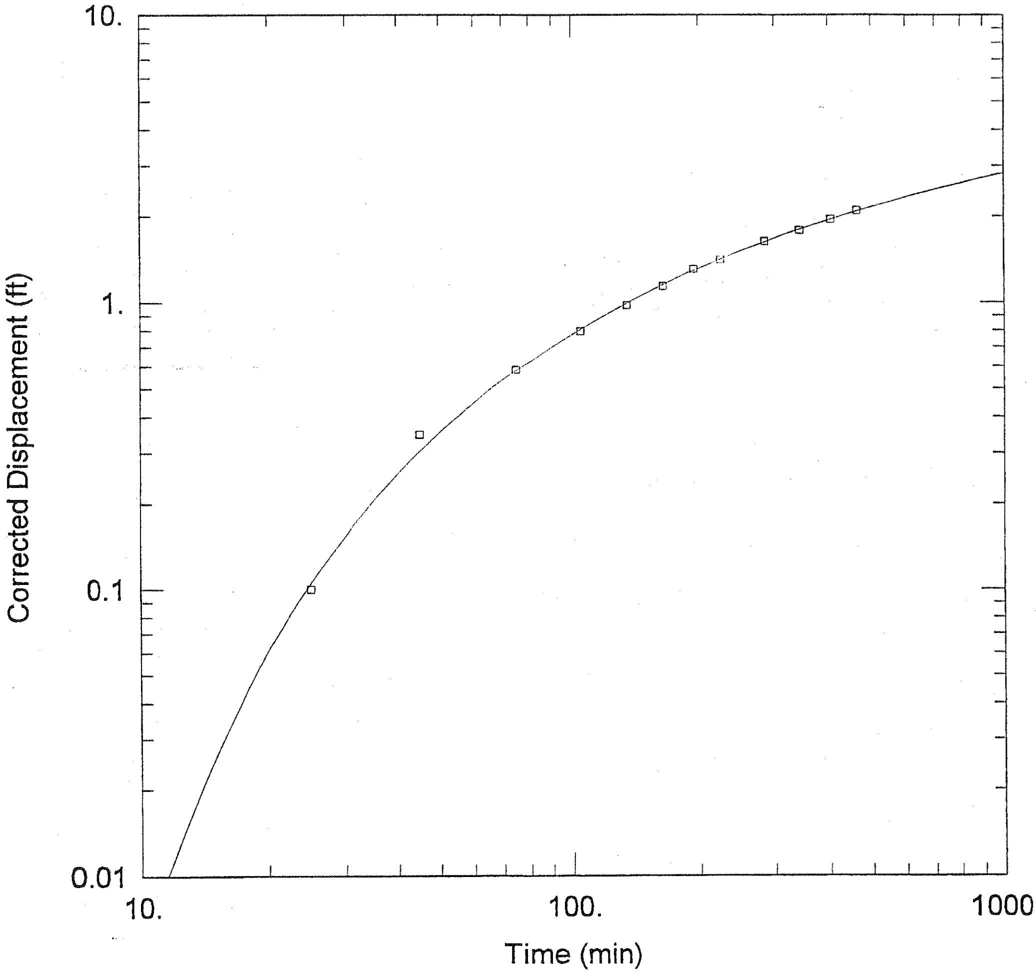
Observation Wells

Well Name	X (ft)	Y (ft)
▫ MW-1	0	-70

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 27.32 ft^2/day
S = 0.001707



WELL TEST ANALYSIS

Data Set: D:\UNC\PUMPTEST\VER1TEST\MW2.AQT
Date: 06/25/98 Time: 17:38:39

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: VER-1
Test Date: 4-30-98

AQUIFER DATA

Saturated Thickness: 20.91 ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
VER-1	0	0

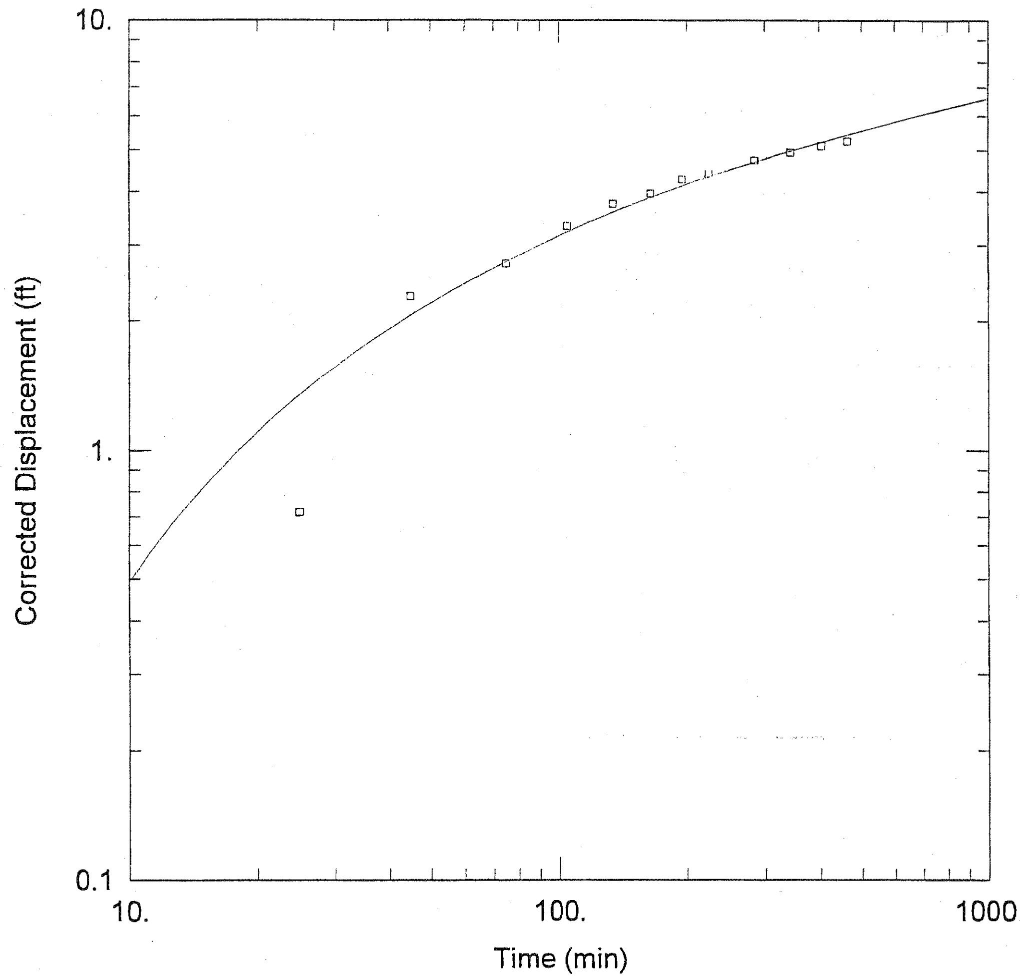
Observation Wells

Well Name	X (ft)	Y (ft)
▫ MW-2	-55	0

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 49.5 ft^2/day
S = 0.001682



WELL TEST ANALYSIS

Data Set: D:\UNC\OWA.AQT
Date: 06/19/98 Time: 15:01:51

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: VER-1
Test Date: 4-30-98

AQUIFER DATA

Saturated Thickness: 20.91 ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
VER-1	0	0

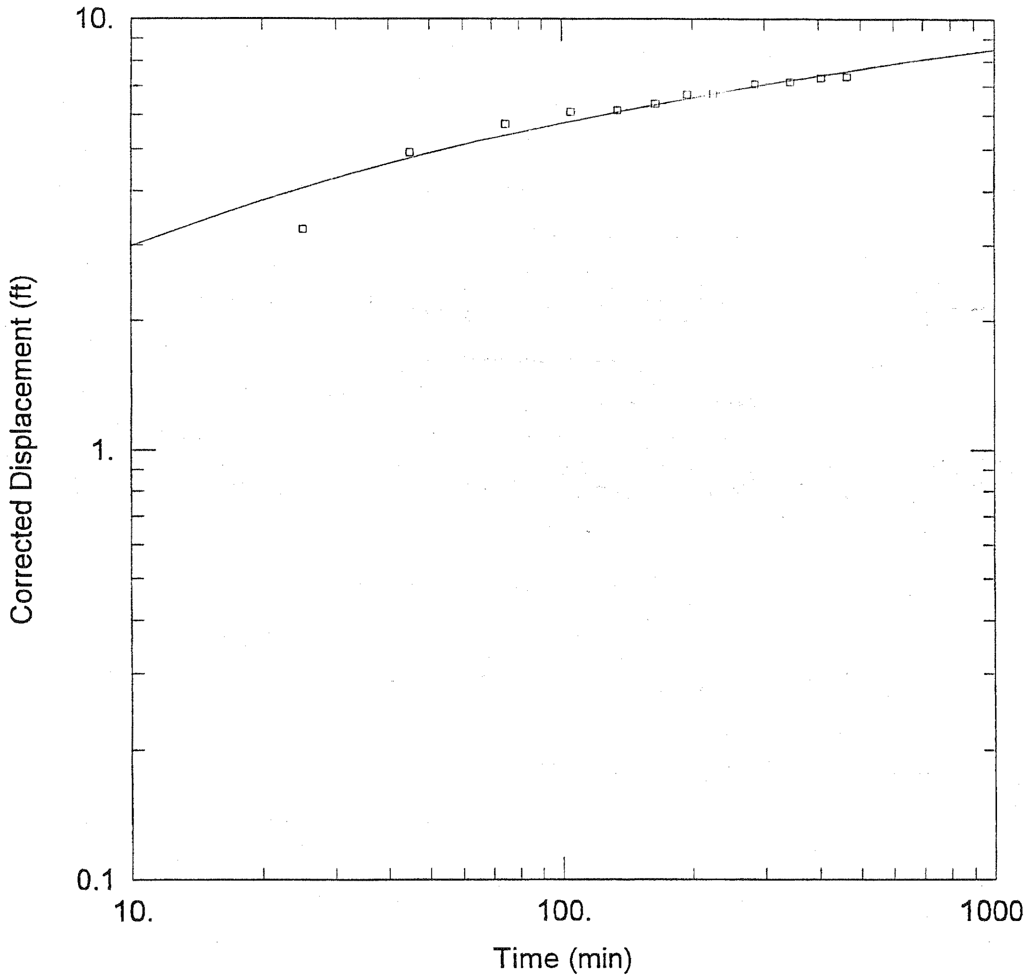
Observation Wells

Well Name	X (ft)	Y (ft)
▫ OW-a	0	-20

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 32.82 ft^2/day
S = 0.001785



WELL TEST ANALYSIS

Data Set: D:\UNC\OWB.AQT
Date: 06/19/98 Time: 14:58:10

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: VER-1
Test Date: 4-30-98

AQUIFER DATA

Saturated Thickness: 20.91 ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
VER-1	0	0

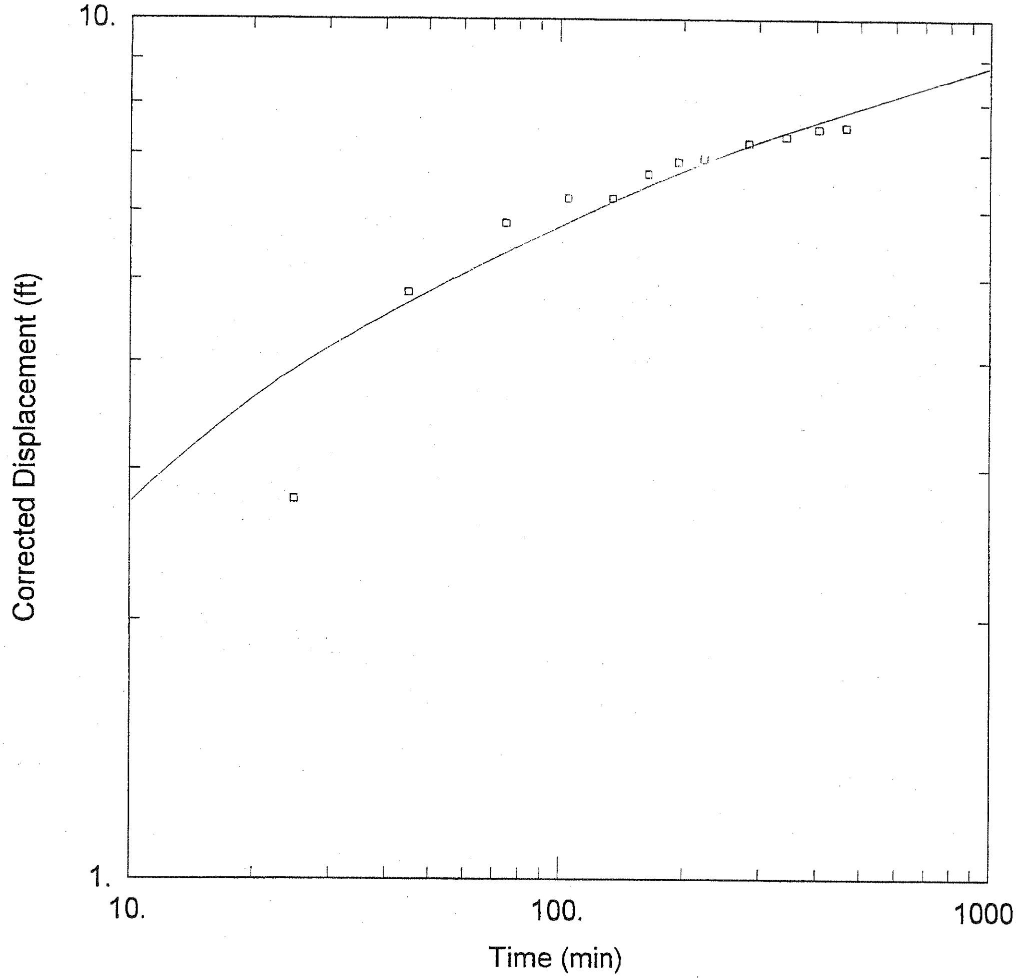
Observation Wells

Well Name	X (ft)	Y (ft)
▫ OW-B	5	0

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

$T = 41.72\ ft^2/day$
$S = 0.00232$



WELL TEST ANALYSIS

Data Set: D:\UNC\OWC.AQT
Date: 06/19/98 Time: 14:29:09

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: VER-1
Test Date: 4-30-98

AQUIFER DATA

Saturated Thickness: 20.91 ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
VER-1	0	0

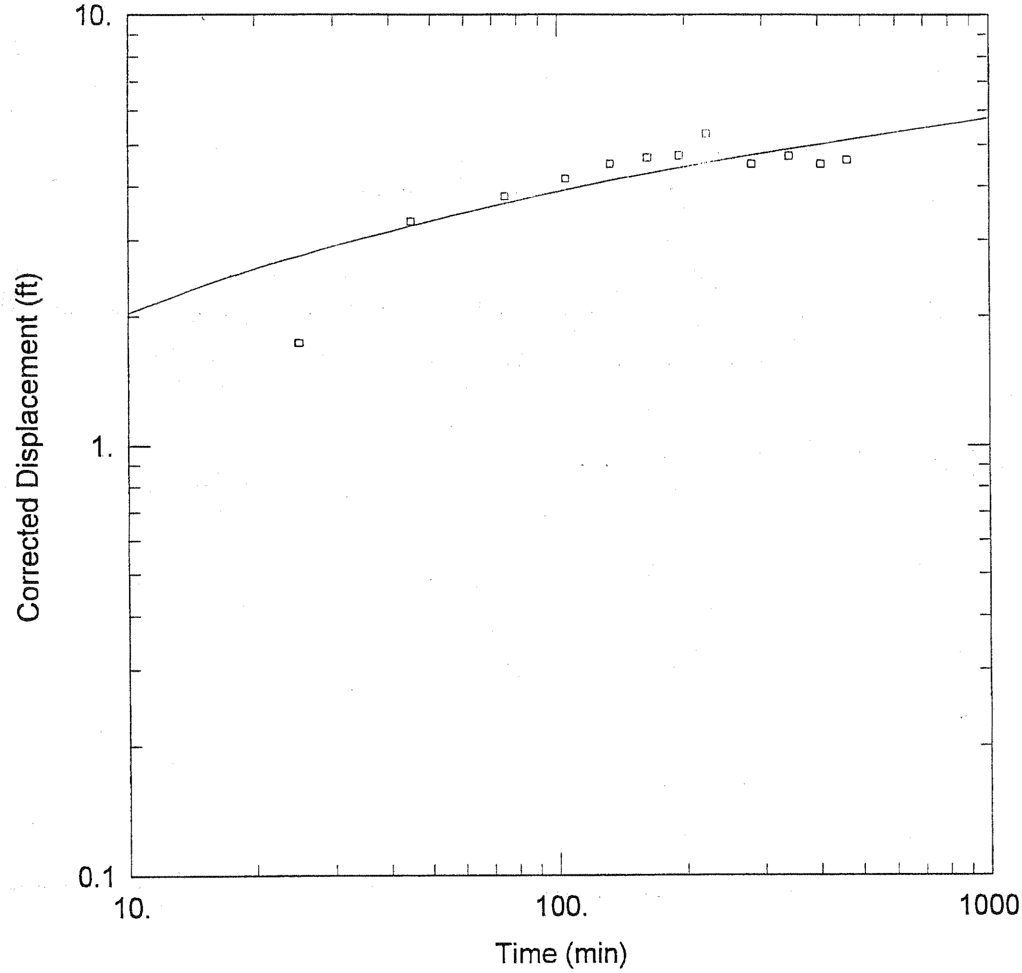
Observation Wells

Well Name	X (ft)	Y (ft)
▫ OW-C	0	5

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 37.46 ft^2/day
S = 0.003328



WELL TEST ANALYSIS

Data Set: D:\UNC\OWD.AQT
Date: 06/19/98 Time: 15:08:02

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: VER-1
Test Date: 4-30-98

AQUIFER DATA

Saturated Thickness: 20.91 ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
VER-1	0	0

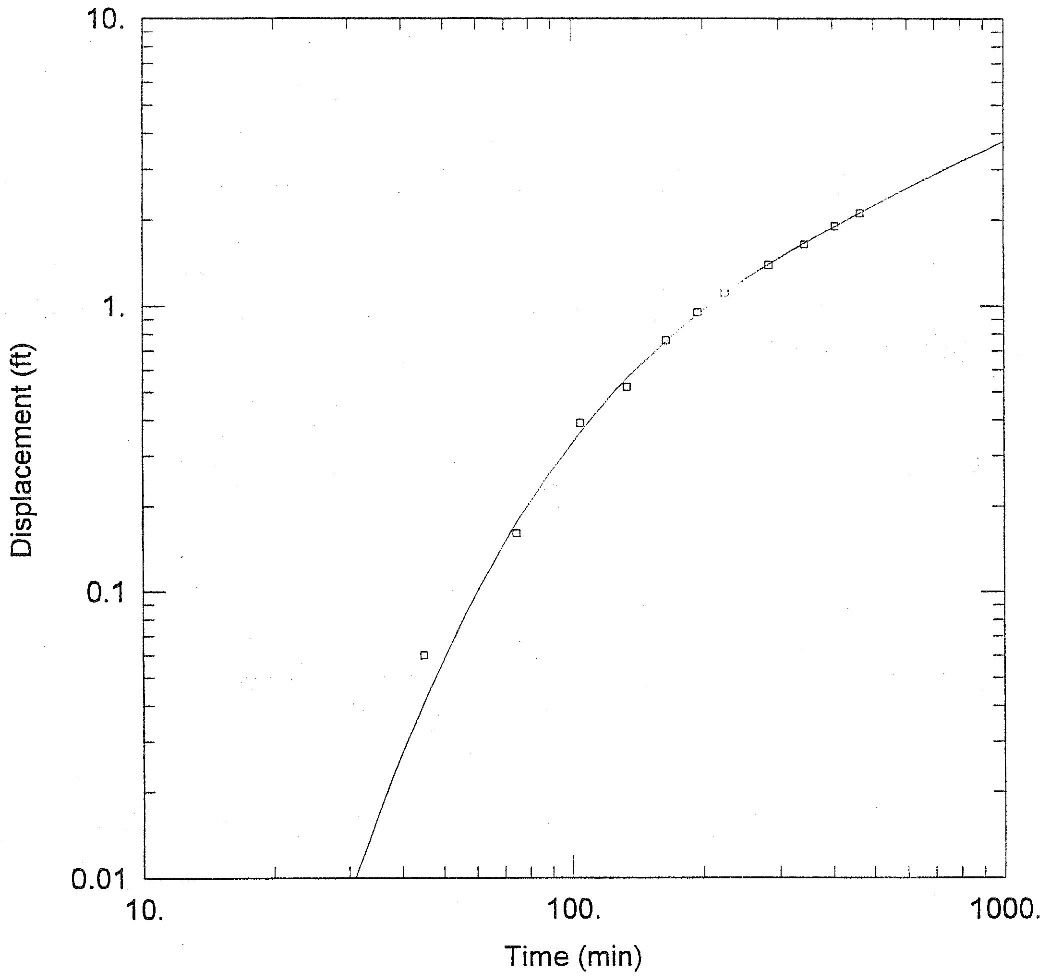
Observation Wells

Well Name	X (ft)	Y (ft)
▫ OW-a	-15	0

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

$T = 61.84\ ft^2/day$
$S = 0.0003756$



WELL TEST ANALYSIS

Data Set: D:\UNC\PUMPTEST\VER1TEST\MW1FR.AQT
Date: 06/26/98 Time: 08:27:27

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: VER-1
Test Date: 4-30-98

AQUIFER DATA

Saturated Thickness: 20.91 ft
Spherical Block Diameter: 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
VER-1	0	0

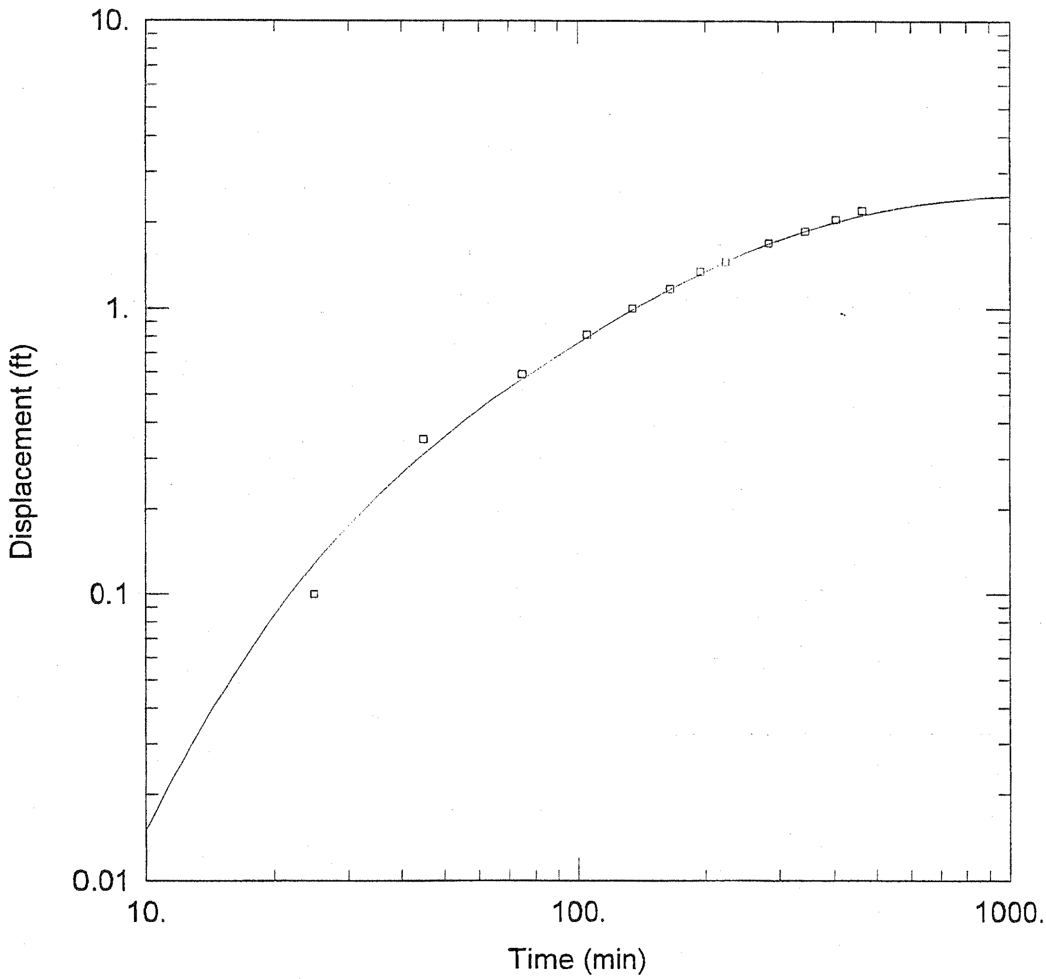
Observation Wells

Well Name	X (ft)	Y (ft)
▫ MW-1	0	-70

SOLUTION

Aquifer Model: Fractured
Solution Method: Moench w/spherical blocks

K = 0.5971 ft/day
Ss = 2.338E-05 ft^{-1}
K' = 0.0001472 ft/day
Ss' = 7.801E-05 ft^{-1}



WELL TEST ANALYSIS

Data Set: D:\UNC\PUMPTEST\VER1TEST\MW2FR.AQT
Date: 06/26/98 Time: 08:32:45

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: VER-1
Test Date: 4-30-98

AQUIFER DATA

Saturated Thickness: 20.91 ft
Spherical Block Diameter: 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
VER-1	0	0

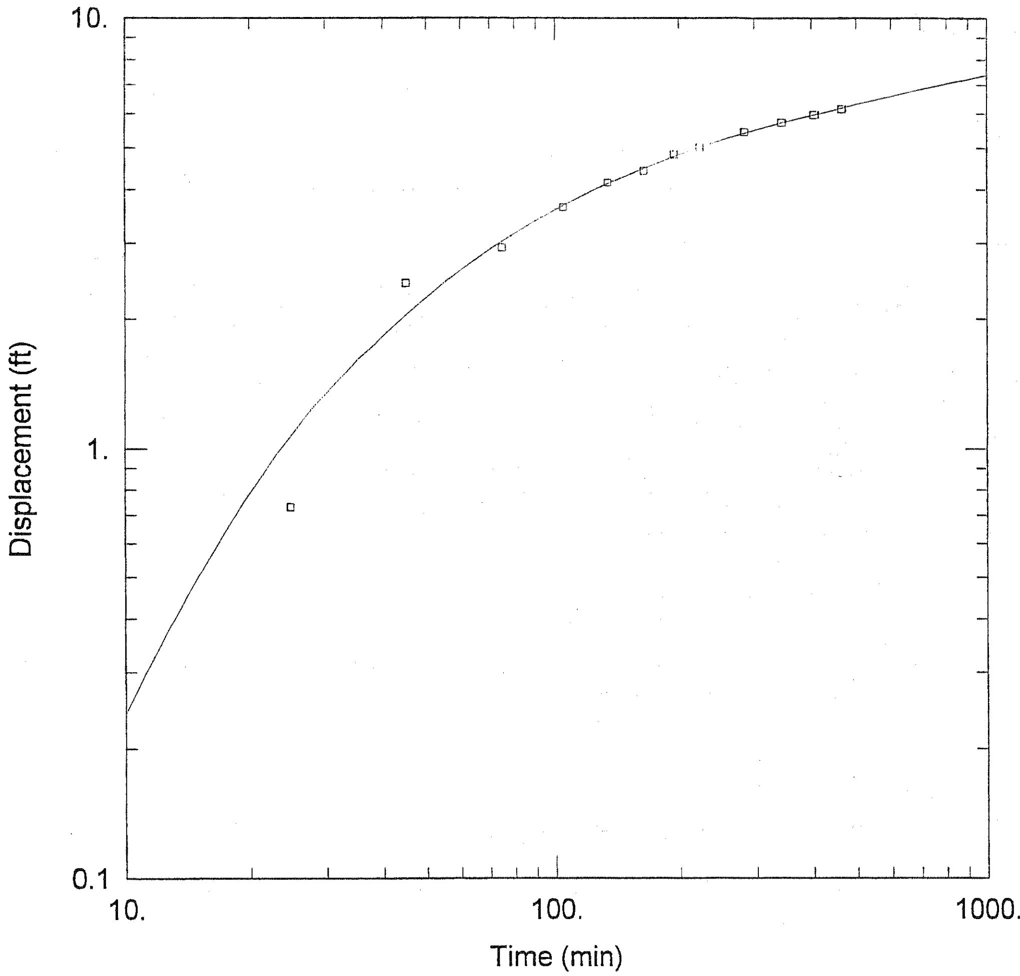
Observation Wells

Well Name	X (ft)	Y (ft)
▫ MW-2	-55	0

SOLUTION

Aquifer Model: Fractured
Solution Method: Moench w/spherical blocks

K = 0.1188 ft/day
Ss = 1.559E-06 ft^{-1}
K' = 5.511E-06 ft/day
Ss' = 1. ft^{-1}



WELL TEST ANALYSIS

Data Set: D:\UNC\OWAFR.AQT
Date: 06/19/98   Time: 15:03:29

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: VER-1
Test Date: 4-30-98

AQUIFER DATA

Saturated Thickness: 20.91 ft   Spherical Block Diameter: 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
VER-1	0	0

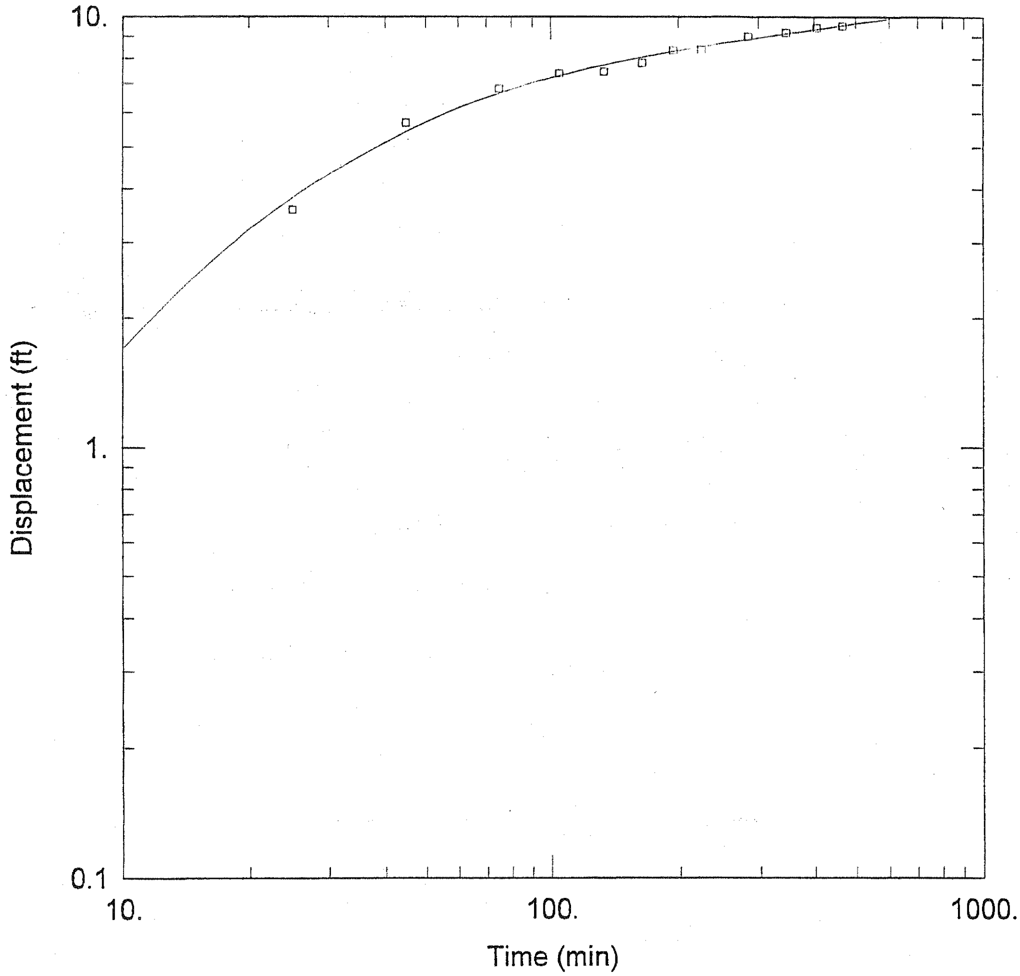
Observation Wells

Well Name	X (ft)	Y (ft)
▫ OW-a	0	-20

SOLUTION

Aquifer Model: Fractured
Solution Method: Moench w/spherical blocks

K = 1.598 ft/day
Ss = 3.979E-05 ft^{-1}
K' = 823.2 ft/day
Ss' = 6.128E-06 ft^{-1}



WELL TEST ANALYSIS

Data Set: D:\UNC\OWBFR.AQT
Date: 06/19/98 Time: 14:58:43

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: VER-1
Test Date: 4-30-98

AQUIFER DATA

Saturated Thickness: 20.91 ft Spherical Block Diameter: 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
VER-1	0	0

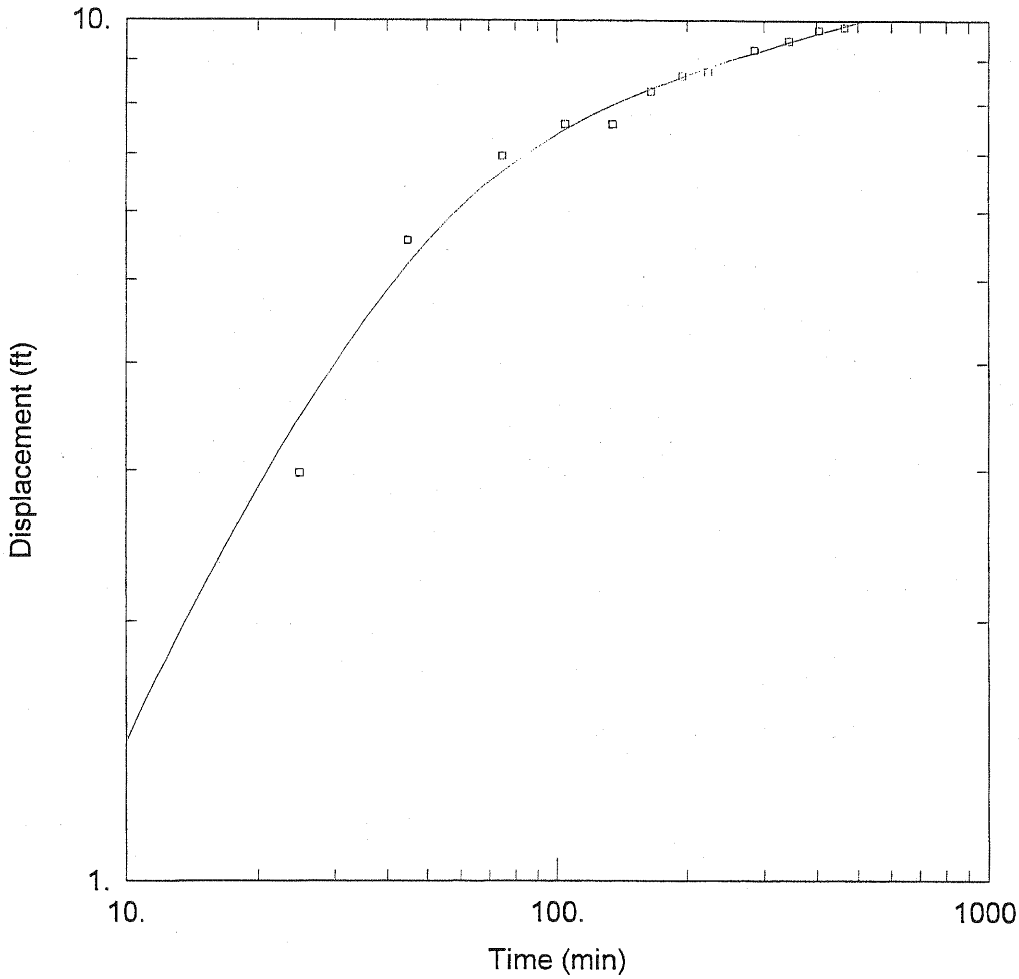
Observation Wells

Well Name	X (ft)	Y (ft)
□ OW-B	5	0

SOLUTION

Aquifer Model: Fractured
Solution Method: Moench w/spherical blocks

K = 1.88 ft/day
Ss = 1.793E-05 ft^{-1}
K' = 719.6 ft/day
Ss' = 1.241E-05 ft^{-1}



WELL TEST ANALYSIS

Data Set: D:\UNC\OWCFR.AQT
Date: 06/19/98 Time: 14:32:06

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: VER-1
Test Date: 4-30-98

AQUIFER DATA

Saturated Thickness: 20.91 ft Spherical Block Diameter: 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
VER-1	0	0

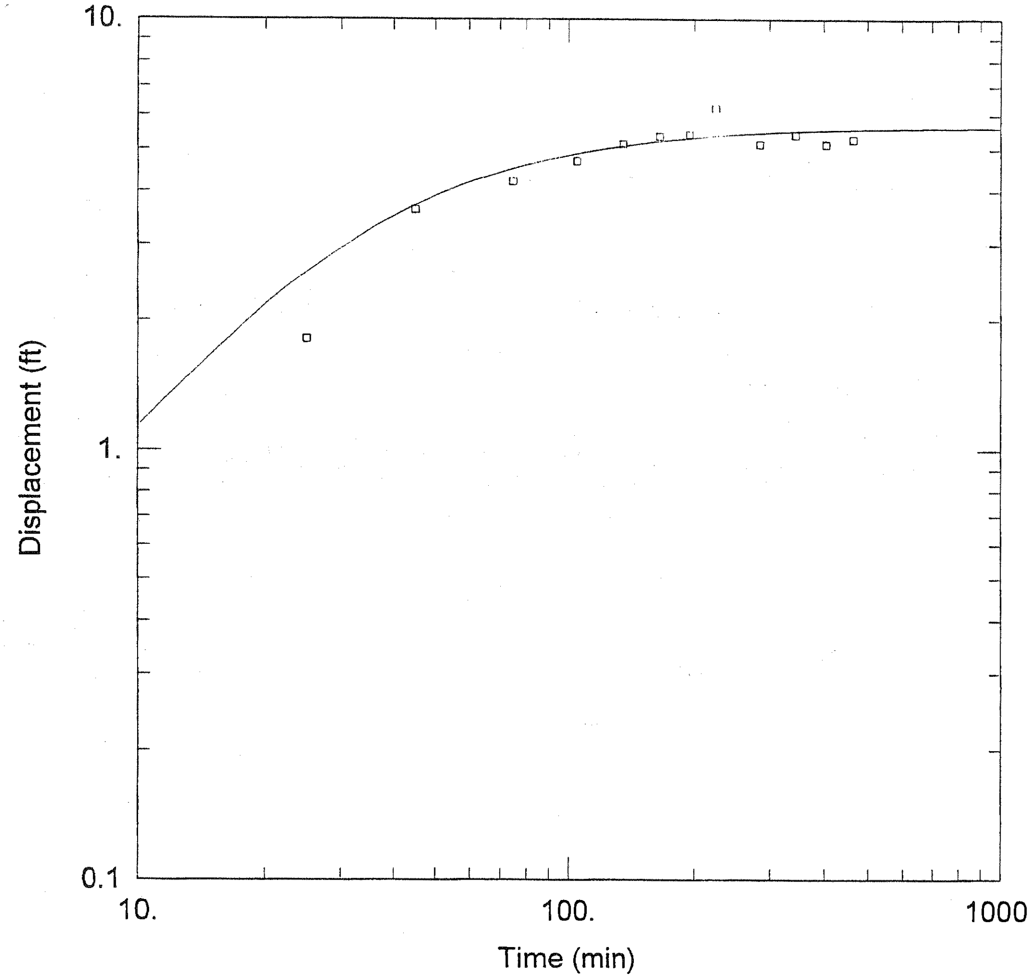
Observation Wells

Well Name	X (ft)	Y (ft)
▫ OW-C	0	5

SOLUTION

Aquifer Model: Fractured
Solution Method: Moench w/spherical blocks

K = 1.921 ft/day
Ss = 1.817E-05 ft^{-1}
K' = 1430.6 ft/day
Ss' = 2.166E-06 ft^{-1}



WELL TEST ANALYSIS

Data Set: D:\UNC\OWDFR.AQT
Date: 06/19/98 Time: 15:07:36

PROJECT INFORMATION

Company: ARCADIS Geraghty & Miller
Client: University of North Carolina
Project: NC000239.0008.MD002
Test Location: Airport Road Site
Test Well: VER-1
Test Date: 4-30-98

AQUIFER DATA

Saturated Thickness: 20.91 ft Spherical Block Diameter: 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
VER-1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ OW-D	-15	0

SOLUTION

Aquifer Model: Fractured
Solution Method: Moench w/spherical blocks

K = 2.923 ft/day
Ss = 3.017E-06 ft^{-1}
K' = 6.735E-07 ft/day
Ss' = 1. ft^{-1}