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TENNESSEE VALLEY AUTHORITY
ENGINEERING LABORATORY

APPLICATION OF THE ELECTROMAGNETIC BOREHOLE FLOWMETER AND
EVALUATION OF PREVIOUS PUMPING TESTS AT PADUCAH GASEOUS DIFFUSION PLANT

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ABSTRACT

Multi-well pumping tests have been conducted at wells MW79, MW108, and PW1 at the Paducah Gaseous Diffusion Plant (PGDP) to determine the hydraulic properties of the Regional Gravel Aquifer (RGA). Soil cores suggest that the RGA consists of a thin sandy facies (2 to 6 feet) at the top of a thicker (> 10 feet) gravelly facies. Previous analyses have not considered any permeability contrast between the two facies. To assess the accuracy of this assumption, TVA personnel conducted borehole flowmeter tests at wells MW108, and PW1. The flowmeter results indicate that a highly permeable zone exists within the sandy facies at wells MW108 and PW1. Well MW79 could not be tested. The high K sand unit is probably 10 times more permeable than comparable zone in the gravelly portion of the RGA.

Previous analyses of the three multi-well aquifer tests do not use the same conceptual aquifer model. Data analysis for one pumping test assumed that leakance was significant. Data analysis for another pumping test assumed that a geologic boundary was significant. By collectively analyzing all three tests with the borehole flowmeter results, the inconsistency among the three pumping tests can be explained. Disparity exists because each pumping test had a different placement of observation wells relative to the high K zone delineating by flowmeter testing.

Knowledge of the general behavior of two-layer aquifer systems, cross flow during a pumping test, and of the location of the high K sand unit in the aquifer, provides the basis of explanation for the multi-well pumping test results. Because some of the wells intersected the high-K unit while others did not, a wide range of drawdown responses occurred which presented problems with analyzing the MW79 pumping test data. Drawdown responses for the pumping test at PW1 resemble those of a confined aquifer because all of the observation wells intersected the high K sand unit. The drawdown responses for the pumping test at MW108 appear to be affected by a geologic boundary because all of the observation wells do not intersect the high K sand unit.

Based on the geologic and K data presented in this report, the correlation between a sandy facies near the top of the RGA and the high K values is very likely. As a result, bulk hydraulic parameters, such as the average K calculated from previous aquifer tests, will underestimate the average migration rates of solutes. Furthermore, groundwater transport processes and the success of any remediation system will be greatly affected by the occurrence and interconnection of the sandy facies.

APPLICATION OF THE ELECTROMAGNETIC BOREHOLE FLOWMETER AND EVALUATION OF PREVIOUS PUMPING TESTS AT PADUCAH GASEOUS DIFFUSION PLANT

CHAPTER I

INTRODUCTION

I-1 Scope of Work

The Tennessee Valley Authority (TVA) was recently contracted by Martin Marietta Energy Systems to conduct electromagnetic (EM) borehole flowmeter testing in the Regional Gravel Aquifer (RGA) at the Paducah Gaseous Diffusion Plant (PGDP) site. The work was performed under Department of Energy Interagency Agreement DE-AI05-920R22053. The objective of this study was to measure the vertical distribution of horizontal flow in four, 2-inch monitoring wells and two high capacity wells with 6-inch and 8-inch diameter slotted well screens under both ambient and pumping conditions.

Flowmeter tests were performed at PGDP in August 1992. At the site, TVA personnel discovered that flowmeter tests could not be conducted for the 2-inch diameter monitoring wells because the electromagnetic flowmeter would not fit inside the wire wound stainless steel screens. Flowmeter tests at the two high capacity wells, however, provided useful information. This report presents the flowmeter data and discusses some of the possible implications to on-going geohydrological investigations at PGDP.

I-2 Borehole Flowmeter Method

Borehole flowmeter tests focus on measuring the vertical distribution of horizontal flow along a screened well or borehole. The measurements are typically performed under ambient and pumping conditions. The flow distributions obtained during ambient conditions provide information on the direction of the vertical component of the hydraulic gradient. Flow distributions measured during pumping provide information on the relative differences of the horizontal hydraulic conductivity of selected aquifer zones.

A sensitive borehole flowmeter enables the user to accomplish two basic functions:

1. It allows the measurement of natural (ambient) vertical flow that exists in most wells; and
2. If the well is pumped at a steady rate, it enables the determination of the flow distribution of groundwater that is entering (or exiting) the well screen from (or to) the surrounding medium.

When subjected to further analysis, item (2) allows the calculation of a horizontal hydraulic conductivity distribution or identification of discrete fractures (or fracture zones) depending on the type of aquifer being assessed.

Shown in Table I-1 is a hypothetical data set typical of that obtained from flowmeter analysis. For this case, the aquifer base is located at $z=0$, and the water table or upper confining layer is located at $z=20$ m. The basic data obtained in the field are the elevations where readings are taken (column [a]), the ambient flow log (column [b]), and the flow log induced by pumping (column [d]). The differential ambient flow (column [c]), the net induced flow log (column [e]), and the differential net-induced flow (column [f]) are then calculated. The data from Table 1 are presented graphically in Figure I-1.

Measurements and calculations are made based on the assumed layered geometry illustrated in Figure I-2. As the figure illustrates, flow to the well is assumed to be horizontal. The basic flow logs (columns [b] and [d]) represent upward or downward vertical flow within the well itself, while the differential flow logs represent horizontal flow in the assumed layers to or from the aquifer media. The sign convention used and advocated in this report is positive for upward vertical flow and horizontal flow into the well, and negative for downward vertical flow and horizontal flow away from the well. The sign convention used in this report is by no means universal. So in any particular application, continuity in sign convention is of utmost importance.

For the example of Table I-1 and Figure I-1, the ambient flow is upward, so the vertical component of the hydraulic gradient vector must point downward (remember the negative sign in Darcy's Law). The differential ambient flow log is obtained by taking differences between neighboring values of ambient flow. As illustrated in Figure I-1(c), flow enters the well at varying rates from the bottom half of the aquifer, and exits the well at varying rates from the top half.

To obtain the total flow log, a pump is turned on, and pumping is continued until flow from each of the assumed layers (e.g., Δz_i ; $i = 1, 2, \dots, n$) that constitute the aquifer is proportional to the transmissivity of the layers. Based on an analysis by Javandel and Witherspoon (1969), this condition occurs when the dimensionless time $t_D = Kt/S_s r_w^2$ is ≥ 100 . In this expression K is the average horizontal aquifer hydraulic conductivity defined as $\sum K_i \Delta z_i / b$, where b is the aquifer thickness, S_s is the aquifer specific storage, t is time since pumping started, and r_w is well bore radius. After t_D is ≥ 100 , which is brief for most aquifers, the total flow log is recorded, including the time after the start of pumping from each measurement, and the drawdown associated with pumping. During a pumping test, the condition for $t_D \geq 100$ can be checked with an estimate of transmissivity and the storage coefficient from an on-going or previous pumping test.

At this stage in the data analysis, a somewhat fine distinction must be made. The drawdown that is measured is due only to pumping. However, the measured flow is due to a superposition of the ambient flow and the pumping-induced flow. Therefore, to be consistent the ambient flow must be subtracted from the total flow to obtain the net flow log. The net flow is that portion of the total flow measured by drawdown. If this subtraction is not made, the results will be ambiguous.

TABLE I-1

Hypothetical data and data analysis related to the application of a borehole flowmeter. Columns (a), (b), and (d) constitute the basic data obtained in the field. Column (e) is column (d) minus column (b). Columns (c) and (f) are differences between the entries in columns (b) and (e) respectively.

Elevation (m)	Ambient Flow (L/min)	Δ Ambient Flow (L/min)	Induced Flow (L/min)	Net Induced Flow (L/min)	Δ Net Induced Flow (L/min)
0	0.00	—	0.0	0.00	—
2	0.05	0.05	0.3	0.25	0.25
4	0.18	0.13	1.0	0.82	0.57
6	0.39	0.21	1.4	1.01	0.19
8	0.60	0.21	1.8	1.20	0.19
10	0.75	0.15	2.5	1.75	0.55
12	0.70	-0.05	2.7	2.00	0.25
14	0.33	-0.37	3.6	3.27	1.27
16	0.17	-0.16	4.6	4.43	1.16
18	0.07	-0.10	5.2	5.13	0.70
20	0.00	-0.07	6.0	6.00	0.87
(a)	(b)	(c)	(d)	(e)	(f)

Figure I-1. Graphical presentation of the data in Table 1. The two plots of differential flow are calculated from the vertical flow data and represent horizontal flow in the aquifer to the test well.

The final column in Table I-1, the differential net flow, is obtained by differencing the net flow log, as illustrated in Figure I-1. This yields the horizontal flow from each assumed aquifer layer due to pumping. Under certain circumstances (Molz et al., 1989; 1990) this flow is proportional to the vertical distribution of horizontal hydraulic conductivity (K) in the vicinity of the test well. It is beyond the scope of this report to present a detailed discussion of how K logs are calculated from differential net flow logs. However, a brief discussion will be presented.

In order to calculate a K profile, two different methods have been discussed in the literature for confined and unconfined aquifers. The first is based on the Cooper-Jacob (Cooper and Jacob, 1946) equation relating drawdown to a constant pumping rate in a fully-penetrating well. The second is based on the numerical results of Javandel and Witherspoon (1969). Molz et al., (1989, 1990) provide an overview of these methods. In some aquifers, the two approaches will provide similar values. However, in aquifers where skin effects exist at the wells and/or large spatial variability exists in the transmissivity field, Young (1993a, b) shows that the second approach is preferred. In general, the second method has a practical appeal because fewer assumptions are required. Additionally, the values for the effective well radius and the storage coefficient of the aquifer (which are impossible to specify precisely) are not required by the second method.

According to Molz et al., (1989, 1990), the numerical results of Javandel and Witherspoon (1969) can be used to develop Equation 1. This equation permits the calculation of a K profile from the information in Figure I-1 given the average K of the aquifer interval of interest. Throughout this report, Equation 1 will be used to estimate the K profile.

$$\frac{K_i}{\bar{K}} = \frac{(\Delta Q_i - \Delta q_i) / \Delta z_i}{Q_p / b} ; i = 1, 2, 3, \dots n \quad (1)$$

where: b = saturated screened aquifer thickness
 K_i = hydraulic conductivity of ith layer
 $\bar{K}$ = average hydraulic conductivity of the screened aquifer interval
 Q_p = total discharge from well during pumping
 ΔQ_i = discharge from ith layer during pumping
 Δq_i = ambient flow from ith layer
 Δz_i = ith layer thickness

CHAPTER II

ELECTROMAGNETIC BOREHOLE FLOWMETER SYSTEM

II-1 Design and Construction

The Electromagnetic (EM) borehole flowmeter system can measure vertical flow in various types of wells and boreholes. The EM borehole flowmeter system has three main components: the downhole flowmeter, the packer assembly, and the above ground electronics. The downhole flowmeter provides accurate flow measurements over a four order-of-magnitude range and fits snugly into a 2-inch, schedule-40 PVC well casing. The packer assembly can be one of several units that attaches to the downhole flowmeter. The above ground electronics operates the hardware in the flowmeter and processes the flowmeter signal to a discharge reading.

Two of the flowmeter's major components are an electromagnet and a pair of chloride electrodes mounted at right angles to the pole pieces of the electromagnet. In operation, the electromagnet creates a strong magnetic field across the flow passage. As water flows through the magnetic field a voltage gradient is generated. The voltage is proportional to the average velocity of the water (the conductor) across the magnetic field and is detected by the electrodes. According to theory, and verified by laboratory tests, the magnitude of the voltage is unaffected by the groundwater's electrical conductivity. The polarity of the voltage generated is dependent on the direction of flow. Upward flow is generally designated as a positive voltage and downward flow as a negative voltage.

The flowmeter used is 30-cm long and has an outer diameter of 4.8 cm. TVA has flowmeters with 1.27-cm and 2.54-cm inner diameters (IDs). The 1.27-cm and the 2.54-cm flowmeters are typically used to measure low range flow rates (10 ml/min to 14 L/min) and high range flow rates (40 ml/min to 40 L/min), respectively. In wells or boreholes with relatively large diameters, the effectiveness of the flowmeter diminishes because of flow around the flowmeter. In order to direct flow through the orifice of the flowmeter in large-diameter wells, a packer assembly is used with the flowmeter. Both a mechanical (Figure II-1) and an inflatable (Figure II-2) packer are available.

The mechanical packer assembly is a collar consisting of a rubber gasket between two plexiglass or steel rings that slips over the flowmeter and is held in place with set screws. The mechanical packer is easily used but its application can be tedious because the friction between the collar and the well makes vertical movement slow. In situations where the well or borehole is uneven, the collar design may not provide an adequate seal and should not be used.

The inflatable packer is a Cherne plug that is usually fastened to a PVC assembly. The packer assembly easily slips onto the flowmeter and is sealed with "O" rings. The packer assembly has an outer

Figure II-1. Mechanical collar and the EM flowmeter.

Figure II-2. Inflatable packer and the EM flowmeter.

diameter of 8.9 cm. If the Cherne plug is slipped directly onto the flowmeter, an 8.7-cm outer diameter (OD) can be obtained. About 15 and 25 psi of pressure are needed to inflate the Cherne plug to diameters of 4 inches and 8 inches, respectively. Inflation is accomplished by injecting water into the Cherne plug through a tube in the flowmeter. Either a pressurized chamber at the ground surface or a submersible pump can be used to inject water into the Cherne plug. For most applications, the submersible pump is the method of choice. However, at shallow depths (< 30 feet) where only a few flowmeter measurements are desired, the pressurized chamber has an advantage in its simplicity and relatively short set-up time.

The above ground electronics includes an electromagnet drive, circuitry to measure the voltage generated by groundwater flow, and computer hardware necessary to output the discharge reading. The electromagnetic drive consists of alternating positive and negative pulses. The signal produced by the electrodes is in the microvolt range and will typically be several orders-of-magnitude less than background noise. Because of the large noise level, synchronous demodulation is used to extract the signal. Synchronous demodulation has the effect of canceling noise out of phase with the electromagnetic drive. With additional amplification and filtering, a DC signal proportional to the water velocity through the down hole body is generated. The electronics collects and processes signals from the flowmeter every second. At the end of one minute, or on manual command, the signals are averaged and the standard deviation is calculated. At the end of a preset time interval, or on command, the average flow value and standard deviation is displayed, stored on disk, and printed to a hardcopy device.

II-2 Laboratory Calibration

Calibration of the EM flowmeters is performed with a set-up at the TVA Engineering Laboratory, Norris, Tennessee. The calibration facility includes standard 5.1-cm, 10.2-cm, and 15.2-cm diameter flush-joint, schedule-40 PVC pipes. Pre- and post-calibration checks are conducted for a range of high and low flow rates using the same EM flowmeter system (above ground electronics, cable, and flowmeter) to be used in the field.

Calibrations are simple and consist primarily of establishing a constant uniform flow through a vertical PVC pipe and comparing the EM flowmeter measurements to flow measurements at the intake and/or the outlet of the PVC pipe. Flow rates greater than 0.5 L/min are established by throttling a pressure valve on the influent water line and measuring the generated flow rate near the PVC pipe intake with an in-line commercial flowmeter. Flow rates less than 0.5 L/min are achieved using a peristaltic pump. For all flow rates, the baseline flow rate is measured using a calibrated volumetric container.

Figures II-3 and II-4 show typical pre- and post-calibration data for the 1.27-cm and 2.54-cm EM flowmeters, respectively. The EM flowmeter data displays good repeatability. One of the major assets of the EM flowmeter is the absence of any moving parts that require adjustment or experience wear that might

1.27 cm FLOWMETER CALIBRATION

Figure II-3. Calibration data for the 1.27-cm ID flowmeter at log and linear scales.

2.54 cm FLOWMETER CALIBRATION

Figure II-4. Calibration data for the 2.54-cm ID flowmeter at log and linear scales.

affect meter calibration. Using a linear correlation between voltage and flow rate, the calibration factor for the 1.27-cm and the 2.54-cm flowmeter with inflatable packer is 1.38 L/min and 3.95 L/min, respectively. The threshold of the 1.27-cm flowmeter is approximately 5 ml/min with an operating range of 10 ml/min to 14 L/min. The threshold of the 2.54-cm flowmeter is approximately 20 ml/min with an operating range of 40 ml/min to an excess of 40 L/min.

At flow rates greater than 10 L/min, two concerns exist with the 1.27-cm flowmeter. One concern is headlosses through the orifice and the other is a flowmeter signal that will exceed the capacity of the electronics. To avoid these problems, the 1.27-cm flowmeter was used for ambient testing and the 2.54-cm flowmeter was used for pumping conditions.

CHAPTER III

FIELD TESTING WITH THE EM FLOWMETER

III-1 Overview

Borehole flowmeter tests include measuring the drawdown and the vertical flow distribution in a screened well or borehole during a constant-rate pumping test. Table III-1 provides a simplified overview of the procedures used to implement the tests.

TABLE III-1 PROCEDURES DESCRIBING BOREHOLE FLOWMETER FIELD TESTS

1. Measure water elevation in the test well and observation wells relative to a reference elevation.
 2. Attach appropriate packer assembly, if any, to flowmeter.
 3. Measure the profile of the ambient vertical flow with flowmeter (typically at least 10 measurements at equal intervals).
 4. Lower pressure transducer below the lowest water elevation anticipated in the well during the pumping test.
 5. Lower pump suction/injection hose into well (hose should be primed and a check/foot valve is recommended).
 6. Remeasure the water elevation in the well.
 7. Begin pumping and measure flow rate with stopwatch and a volumetric container.
 8. Record drawdown with a pressure transducer system until the water elevation in the well stabilizes--occasional manual water level measurements should be taken, if possible.
 9. Measure profile of vertical flow after water elevation has stabilized with flowmeter (using the same interval spacing used for the ambient measurements).
-

III-2 Flowmeter Measurements

The borehole flowmeter should be connected to the electronics and at least 30 minutes allowed for electronic circuitry to warm up. If possible, the flowmeter is lowered to a location in the well where there is no ambient flow to check its calibration at zero flow. In a non-artesian well, ambient flow should not exist above or below the screened interval. In a borehole, no ambient flow should occur in the cased interval above the borehole. If there is doubt concerning the location of a no flow zone, the problem is resolved by temporarily plugging the flowmeter and lowering it into the well. Once the flowmeter's calibration has been checked at a no flow interval, the ambient flow measurements are logged.

An important aspect of the pumping test is the pumping rate. The pumping rate must be high enough to produce measurable drawdown and a measurable flow distribution in the well, but low enough to prevent excessive drawdown and flow rates in the well. The problems associated with selecting a constant flow rate are particularly acute in aquifers with either high or low transmissivities. For example, in aquifers possessing low transmissivities the rate of drawdown can be significant in affecting the lift requirements and subsequent performance of most pumps. If pumping rate adjustments are not made as the drawdown increases, the discharge rate will decrease until the drawdown stabilizes.

During a pumping test, drawdown data is collected with a pressure transducer connected to a data logger that records pressure at 1- to 2-second intervals. Movement of the flowmeter during pumping tests will sometimes produce fluctuations in the measured pressures. This occurs because movement of the flowmeter cable often jiggles the transducer and/or introduces a temporary pressure change in the well. To avoid unnecessary complications with the data analysis, approximately 30 minutes is required between the start of the pumping and flowmeter measurements. If drawdown data is required from the time period of flowmeter measurements, selective editing of the data may be necessary to remove erratic fluctuations.

III-3 Selection of Pumps

The type of pump used for the test depends on the well specifications and power availability. If the depth of the water from the top of casing will not exceed approximately 30 feet, then a surface pump may be used. Several types of pumps have been used by TVA. For flows greater than 4 L/min, centrifugal surface pumps have proven to be the most reliable. This pump type is tolerant of suspended solids and high or blocked discharge pressures, has good lift, and can cover an order-of-magnitude flow range by manually adjusting the back pressure. A disadvantage of the centrifugal pump is the difficulty of presetting the pump to a known rate. For flows less than 4 L/min a peristaltic pump might be considered a good choice. It is easy to use, there is no contamination of the pump, and it may be preset to reasonable tolerances.

Dissolved gasses in groundwater can be a problem with surface pumps. The suction line pressure will be the lowest on the surface near the pump. This can result in degassing and a potential exists for the creation of an air block. It is important in these situations to have the pump elevated above the well head and have no dips in the suction line. In this situation, any out-gassing will flow through the pump and will not collect in the hose.

If the depth of water exceeds the lifting capabilities of the surface pump, then submersible pumps are required. Submersible pumps have not been thoroughly investigated by TVA. The selection has been based primarily on size. The outside diameter of the pump must be sufficiently small to fit into the well containing cables from the flowmeter and pressure transducer.

TVA has used two types of submersible pumps: a 24-volt DC Fultz[™] pump and a variable frequency AC Grundfos[™] pump. The Fultz[™] pump will operate from a 24-volt DC supply or two automotive batteries. Speed or flow rate is controlled by varying the voltage or with a rheostat. The Grundfos[™] pump requires a 220 VAC supply (a new version is available that requires 115 VAC) and a frequency controller and will pump at a rate much higher than the Fultz[™] pump. The pumping rate of both units depends on the vertical lift. As the water level in the well drops, the lift increases and the pumping rate will decrease. Both of these submersible pumps have diameters of approximately 5.1 cm. Flowmeter tests in a 5.2-cm well with a water table greater than 6 meters requires water injection. For testing at PGDP, the Grundfos[™] pump was used.

CHAPTER IV

SITE DESCRIPTION

IV-1 Site Location and Geology

The PGDP is a uranium enrichment facility located on a 960-acre reservation in western McCracken County. Construction of the plant began in 1951. Uranium enrichment began in 1952. PGDP is about 3 miles south of the Ohio River and about 10 miles west of Paducah, Kentucky (Figure IV-1). A variety of hazardous, nonhazardous, and radioactive wastes have been generated as a result of plant operations. Large-scale, multiple pumping tests have been conducted at wells MW108, PW1, and MW79 (Figure IV-2).

PGDP is located in the Jackson Purchase region of the Gulf Coastal Plain physiographic province near the northern margin of the Mississippi Embayment. The Mississippi Embayment was a large sedimentary trough oriented approximately north-south that existed during Cretaceous and Tertiary time. The embayment received sediments shed off the central part of the North American continent. The sedimentary sequence at PGDP consists primarily of fine- to medium-grained clastic materials including (from oldest to youngest) a basal gravel (i.e., Tuscaloosa Formation), the McNairy Formation, the Porters Creek Clay, and undifferentiated, discontinuous Eocene sands. These strata dip gently to the southwest toward the axis of the Mississippi Embayment.

Following their deposition, the embayment sediments were either uplifted and/or sea level was lowered resulting in the development of an erosional surface that truncated the sediments. Subsequently, during the late Tertiary and Quaternary time a formational unit designated as the Continental Deposits was laid down in the region creating an angular unconformity with the underlying sediments. Immediately overlying the Continental Deposits, Pleistocene loess (originating as wind-blown material generated by glacial activity to the north) was deposited in a layer of variable thickness. Figure IV-3 shows a schematic cross section illustrating the regional stratigraphic relationships.

The Continental Deposits are of most interest to groundwater investigations at PGDP. These deposits originated from a large low-gradient alluvial fan that covered most of the region and eventually buried the erosional topography. The alluvial fan was formed during the Miocene(?)–Pliocene epoch and was caused by increased flow and large sediment loads in the ancestral Tennessee River, which occupied approximately the same position as the present day Tennessee and Ohio Rivers (Olive, 1980). Erosion and reworking of the alluvial fan deposits during the Pleistocene resulted in the present thickness and distribution of the Continental Deposits.

Valley alluviation occurred during interglacial stages and erosion and entrenchment during glacial stages. The paleovalley fill sequence began with deposition of coarse sand and gravel in a braided fluvial environment. A braided fluvial system resulted from moderate stream gradients and an abundance of

Figure IV-1. Map showing the location of PGDP in relationship to the geographic region.

Locations of aquifer test sites at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky.

Figure IV-2. Location of three pumping tests at PGDP.

GENERALIZED NORTH-SOUTH SECTION SHOWING
REGIONAL STRATIGRAPHIC RELATIONSHIPS
(NOT TO SCALE)

Figure IV-3. Generalized north-south section showing regional stratigraphic relationships.

bedload material derived from Pliocene alluvial fan deposits (Clausen, et al, 1992). As aggradation of the fluvial system continued, stream gradients in the ancestral Tennessee River and tributaries lessened. Lower gradients favored a transition from a braided environment to a meandering environment. The transition is recognized in the subsurface with very gravelly lower sequences becoming more sandy upwards. Later during the Pleistocene, widespread lacustrine sedimentation occurred along the ancestral Tennessee River Valley, resulting in deposition of predominantly fine-grained sediments comprising the upper continental deposits. Because of its bimodal nature, the Continental Deposits have been subdivided into a lower unit (gravel facies) and an upper unit (clay facies) (EDGE, 1989; CH2M Hill, 1992). The basal sandy gravel facies of the Continental Deposits is referred to as the Regional Gravel Aquifer (RGA) and forms the uppermost or "first encountered" useable aquifer (Terran, 1992).

Investigators have found lower gravel facies occurring at predominantly three horizons at PGDP. The most prominent and deepest of these horizons consists of Pleistocene fluvial deposits on an erosional surface at an average elevation of 280 feet amsl. These deposits occur north of a buried terrace on an erosional surface with elevations varying from approximately 245 to 310 feet amsl. The upper surface of these gravel deposits occurs at an average elevation of 310 feet amsl. The Pleistocene gravel deposits have an average thickness of approximately 30 feet (DOE Groundwater Monitoring Phase III).

IV-2 Previous Pump Test at PW1

A 72-hour constant rate pumping test at 92 gal/min was performed at PW1 in June 1991. A detailed description of the test and the data analysis is presented by CH2M Hill (1992). Figure IV-4 shows the areal and vertical locations of the pumping and observation wells. Each well was constructed with a sand pack to five feet above the screen, a bentonite seal approximately five feet thick above the sand pack, and grout in the annular space above the bentonite seal (CH2M Hill, 1992). The primary observation wells are located in the RGA. Shallow wells were also located in the upper aquifer so that any leakage through the clay facies to the RGA could be estimated by matching a set of type curves for unsteady flow in a leaky confined aquifer to the drawdown data. The type curves used in the analysis were developed by Cooper (1963) and obtained partially from Lohman (1978).

Type curve matches were made to both the pumping and the recovery curves. In addition, the Cooper-Jacob Straight-Line (CJSL) Equation (Cooper and Jacob, 1946) was applied to the drawdown data. None of the shallow piezometers developed drawdown curves suitable for matching. Of most interest to this study are the estimated transmissivity values, which are presented in Table IV-1. With the exception of well PZ-4G, all three analyses for the wells provided very similar results. CH2M Hill (1992) suggest that PZ-4G may be screened in a region of lower hydraulic conductivity and/or may exhibit significant positive

Figure IV-4. Well network for PW1.

skin effects due to improper well installation; because the well was not considered to be properly screened in the RGA.

TABLE IV-1. CALCULATED TRANSMISSIVITY VALUES FROM THE PW1 PUMPING TEST (FROM CH2M HILL, 1992)

Well	Transmissivity (ft ² /day)		
	Leaky Analysis Drawdown Data	Leaky Analysis Recovery Data	CJSL Equation Drawdown Data
PZ-1G	6,405	7,046	6,765
PZ-2G	6,405	6,710	6,494
PZ-3G	5,872	6,127	4,059
PZ-4G	1,281	1,084	Not Conducted
PZ-5G	5,872	6,405	6,494
Average*	6,138	6,572	5,953

*does not include Well PZ-4G

In Table IV-1 the results of the type curves analyses for leaky aquifers and the CJSL Equation compare favorably. If leakance were a primary effect on the drawdown curves, then the CJSL Equation should overestimate the transmissivity values. The good agreement exhibited among the transmissivity values suggests that leakance may be difficult to quantify given its small effect on the calculated transmissivity values at each well and the known spatial variability of the RGA aquifer and adjacent aquitards.

IV-3 Pump Test at MW108

A 72-hour constant rate pumping test at 141 gal/min was performed at MW108 in April 1992. A detailed description of the test and the data analysis are presented by Terran (1992). Figure IV-5 shows the areal and vertical locations of the pumping and observation wells. Each well was constructed with a sandpack to five feet above the screen, a bentonite seal approximately five feet thick above the sand pack, and grout in the annular space above the bentonite seal (PGDP personnel). The primary observation wells are located in the RGA. Shallow wells were also located in the upper aquifer so that any leakage through the clay facies to the RGA could be estimated by matching a set of type curves for unsteady flow in a leaky confined aquifer to the drawdown data. The analyses used included: the Theis Equation (Theis, 1935) for

Figure IV-5. Well network for MW108.

confined aquifers, the Jacob (1947) "leaky aquifer" Equation as modified by (Ferris et al., 1962), and the Cooper-Jacob Straight-Line Equation (Cooper and Jacob, 1946).

An obstacle to a proper analysis of the pumping test data is an anomalous change in the slopes of the semi-log drawdown plots near 400 minutes (Appendix C). This change suggests that the aquifer is nonuniform as illustrated in the different early and late time slopes of the semi-log plots. An implication of this change is that an accurate value for leakance cannot be obtained by type-curve matching with leaky aquifer type curves.

Previous results from PW1 suggest that leakance may be small enough such that credible values for transmissivity could be obtained using a Theis curve analysis and/or the CJSJL method. Dividing the drawdown curves into early and late times with respect to the change in slope, Terran (1992) calculated the transmissivity values using the Theis and CJSJL Equations (Table IV-2). By imposing several assumptions at late and early times, Terran (1992) estimates leakance based on some simplifying assumptions at late and early times.

TABLE IV-2. CALCULATED TRANSMISSIVITY VALUES FROM THE MW108 PUMPING TEST (FROM TERRAN, 1992)

Well	Transmissivity (ft ² /day)			
	Theis Type-Curve		CJSJL Equation	
	Early Time	Late Time	Early Time	Late Time
PZ109	56,900	12,900	49,400	13,300
PZ110	42,400	12,400	45,100	14,000
PZ117	48,500	13,400	46,800	12,900
PZ118	59,000	11,400	53,200	13,200
PZ107	57,600	10,100	47,400	11,200
Average	52,880	12,040	48,380	12,920

Note: All wells except PZ107 are less than 150 feet from MW108. Well PZ107 has a radius of 438 feet. The CJSJL Equation is not valid for early time less than 400 minutes at well PZ107.

The reliability of the MW108 pumping test interpretation by Terran (1992) is directly related to an assumption of a uniform aquifer and, in particular, with the explanation for the five-fold difference in the slope of the semi-log drawdown curve at early and late times. Terran (1992) suggests that the cause for the slope change is likely a change in the thickness in the aquifer or a reduction of its permeability with distance.

Terran (1992) shows that a reduction in transmissivity approximately 900 feet south of the pumping well would cause an increase in the drawdown slope near 400 minutes. However, there is no evidence to suggest that a reduction in transmissivity at this distance could produce the responses similar to that observed in the observation and pumping wells.

The drawdown data for the pumping well does not exhibit changes in its semi-log slope that correspond to those of the observation wells. Instead, the drawdown response of well MW108 is more similar to a Theis curve, thereby casting doubt on a reduction in transmissivity with distance. Extensive analysis of several pumping tests in a fluvial aquifer (Young and Herweijer, 1992) demonstrates that changes in transmissivity of the aquifer with distance affect both the drawdown curves at the observation wells and at the pumping well (Appendix A). Another problem with crediting a transmissivity change for the drawdown trends at the observation wells is that an even no-flow boundary condition at 900 feet significantly underpredicts the increase in the slope (to be discussed in more detail later). These issues suggest that the assumptions underlying the analysis by Terran (1992), and CH2M Hill (1992), by analogy, are questionable. As shown in the following chapters, the RGA possesses vertical heterogeneity significant enough to cause problems with the standard practice of type-curve matching.

CHAPTER V

FLOWMETER TESTS

V-1 Flowmeter Logs

Figure V-1 summarizes the result of the flowmeter survey during ambient and pumping conditions for wells PW1 and MW108. The flow profile is measured at depths relative to the top of well casing (TOC). The flowmeter results at wells PW1 and MW108 are very similar (Figure V-1 and Appendix B). This is somewhat surprising because of the complex fluvial geology of the site and the interwell distance of about 3,000 feet.

Flowmeter profiles of ambient conditions occur in response to aquifer boundary conditions and spatial variability in the aquifer's hydraulic properties. Both wells exhibit only upward flow under ambient conditions. If the RGA is semi-confined to confined by lacustrine clay deposits (which is presumed based on geologic data and the results of multi-well pumping tests), then the main cause for upward ambient flow is not from surface effects such as large evaporative losses, but rather aquifer heterogeneity. Aquifer heterogeneity can cause divergent and convergent groundwater flow patterns. In such cases, slightly lower hydraulic pressures occur in localized units of high hydraulic conductivity.

An important feature of the flowmeter profiles for pumping conditions is the high inflow near the upper two to three feet of the screened interval. Based on the relationship shown in Equation I-1, this comparison indicates that the hydraulic conductivity of this upper zone is at least 10 times greater than that of any other unit intersected by the well screen. Important questions regarding the highly permeable sediments at the two wells are their upper bound and whether they are a part of a contiguous and continuous geologic unit. The overall similarities in the flowmeter profiles for ambient and induced flow conditions between the two wells are striking. Although the data is considered sparse, one must consider the possibility of large-scale geologic features that might be responsible for these similarities.

V-2 Drawdown Data

During each of the pumping tests, pressure transducers were used to measure the drawdown response of the test wells. The equipment set-up included a 5 psi Druck pressure transducer connected to a Telog single-channel data logger. Drawdown values were recorded at 2-second intervals throughout the pumping test. Approximately 15 minutes into each pumping test, flowmeter measurements began. The target pumping rates for wells PW1 and MW108 were 17 and 19 L/min, respectively. Figure V-2 presents the drawdown results and discharge measurements.

The drawdown data for PW1 was edited to remove several 8-second periods where fluctuations occurred in the drawdown measurements because of the flowmeter's movement. A linear regression of the

Figure V-1. Flowmeter results for wells PW1 and MW108.

Drawdown Response During Borehole Flowmeter Tests

Figure V-2. Drawdown response at wells PW1 and MW108 during borehole flowmeter tests.

semi-log plot for the PW1 data from 50 to 2000 seconds provides a slope of 0.0408. With this slope the CJSJL Equation provides a transmissivity of 3,440 ft²/day. This value is consistent with the transmissivity values near 6,000 ft²/day determined from the pumping test at PW1 (Table IV-1).

The drawdown data for MW108 also is presented in Figure VI-2. The lack of any usable trend resulted from several factors. The primary problem is that the well was not adequately stressed during the pumping test. Additionally, the small amount of drawdown was at or below the sensitivity of the pressure transducer. The low aquifer response, coupled with the problems experienced from using a pressure transducer while moving the borehole flowmeter, resulted in an unusable drawdown data set.

CHAPTER VI

HYDRAULIC CONDUCTIVITY VALUES

VI-1 Transmissivity Values

The use of Equation 1 with flowmeter data requires a value for $\bar{K}$, the average K for the aquifer material intersected by the well screen. Typically, $\bar{K}$ is calculated from the transmissivity obtained by analyzing the drawdown data from the borehole flowmeter test. However, $\bar{K}$ could as well be calculated from comparative methods, which includes transmissivity values from other pumping test other than that for the flowmeter test. At both PW1 and MW108, the previous pumping tests provided useful drawdown data.

Figure VI-1 shows the drawdown response at wells PW1 and MW108 during the pumping tests described in Chapter 4. The data were obtained by digitizing the drawdown curves presented in the aforementioned reports. In analyzing the data, the goal is to calculate transmissivity reflective of the aquifer material near the pumping well and to avoid problems associated with boundary conditions. In order to achieve these goals, the early portion of the data set was used in the analysis. For both data sets, this time period was limited to 100-1000 minutes. For well PW1, the leveling off of drawdown values after 100 seconds and the declining drawdown values after 1000 seconds is of concern. CH2M Hill (1992) reports that PW1 had a constant pumping rate of 92 gal/min which is inconsistent with the observed drawdown. However, CH2M Hill (1992) does not address this potentially important inconsistency that may be real and have implications in the analysis of the PW1 pumping test. The assumption is made that measurement error is responsible for the declining drawdown values.

One should note, that for this pump test, the rate of change in the drawdown response at the observation wells increases at late times. However, the semi-log plot of drawdown data for the pumping well (MW108) does not exhibit this same behavior. The disagreement between the trends in the drawdown response in the pumping and the observation well was not addressed by Terran (1992). As will be shown later, we believe this disagreement is important to the analysis of the well MW108 pump test.

There are several methods available for calculating transmissivity from the drawdown data of single well tests. If applicable, the CJS� Equation is the method preferred by the authors. The results from Tables IV-1 and IV-2 indicate that the CJS� Equation is appropriate for this analysis. For the PW1 drawdown data, the slope of the semi-log plot between 1 and 1000 minutes is 0.35. Using the straight-line method, the resulting transmissivity is 9,300 ft²/day. This transmissivity is within a factor of 3 of the 3,440 ft²/day calculated from the borehole flowmeter pumping test.

For well PW1, the transmissivity will be set to 6,400 ft²/day which is an average of the two values above and a value in excellent agreement with the transmissivity values in Table IV-1 (for the observation wells near PW1). For the MW108 drawdown data, the slope of the semi-log plot between 1 and

72-hour Pumping Test Results

Well PW1

Well MW108

Figure VI-1. Drawdown response at wells PW1 and MW108 during previous pumping tests.

1,000 minutes is 0.25. Using the straight-line method, the calculated transmissivity is 19,700 ft²/day. This value lies between the average transmissivity values of 53,000 and 13,000 ft²/day for late and early times, respectively, in Table IV-2.

VI-2 Hydraulic Conductivity Profiles

At well PW1, K is calculated as 160 ft/day using the transmissivity of 6,400 ft²/day across a 40-foot screen. At well MW108, K is calculated at 660 ft/day given a transmissivity of 19,700 ft²/day across a 30-foot screen. Using the net differential flowmeter profiles in Figure V-1, Equation 1 is used to calculate the K profiles for the two wells as shown in Figure VI-2. It is important to note that the K values shown in the figure represent horizontal hydraulic conductivity values.

According to sediment boring logs obtained for well MW108, an 8-foot thick, well-sorted, silty, fine- to medium-grained sand, resides at the top of the RGA at this location (Figure VI-3). The highest K value measured during flowmeter testing, about 7,200 ft/day, is located within the sand unit. This K value is about 2.5 times higher than the upper most value of that provided by Freeze and Cherry (1979) for silty sand and corresponds better to that of a clean sand. K values for the RGA below 73 feet range from <7.2 to 450 ft/day. The lower value of <7.2 ft/day is based on the resolution of the flowmeter and possible problems associated with proper well development and installation within a 3-foot layer. Three sediment units reside at depths of 80, 84-90, and 94 feet that have K values of 410, 320-450, and 415 ft/day, respectively. These sediments might be interpreted as sand units that are relatively devoid of gravel. The units are therefore better sorted giving rise to larger and more interconnected pores. The units might also represent lenses of clean, clast-supported gravel; however, gravel of this nature would exhibit much higher hydraulic conductivities.

The highest K value measured for well PW1 is 1,600 ft/day for a 3-foot layer at the top of the RGA (60 to 63 feet deep). Lack of soil core data at PW1 prevents a correlation with any sand unit. Evidence for a possible correlation exists at the closest soil log at PZ-4G located approximately 32 feet from PW1 (CH2M Hill, 1992). At well PZ-4G, a 1-foot clean sand unit was identified above the RGA gravel aquifer at a 55-foot depth. Based on the flowmeter results (Figure VI-2), the deposits in the gravel RGA unit at depths between 63 and 100 feet have K values from <1.6 to 250 ft/day.

In analyzing the borehole flowmeter results, one must understand that well development and construction has an effect on the localized flow patterns near the well. In particular, the 5-foot interval where the sand packs extend above the well screens may very well serve as a conduit for groundwater flow from a permeable unit into the well. As a result, the assumption of converging flow, rather than horizontal flow near the top of the well screens, may be more approximate. Therefore, the K values calculated for the upper intervals at both wells PW1 and MW108 are likely biased.

Horizontal Hydraulic Conductivity Profiles

PW1

MW108

Figure VI-2. K profiles at PW1 and MW108 by the borehole flowmeter method.

Figure VI-3. Generalized geologic profile at MW108.

CHAPTER VII

DISCUSSION OF RESULTS

VII-1 Problems With an Assumed Geological Boundary for the MW108 Pumping Test

The changes in the slopes of the semi-log drawdown plots in Appendix C pose a serious problem to any analysis. Terran (1992) investigates the possibility of a linear geological boundary condition using image wells. Terran (1992, page 51) states "that there is evidence that the cone-of-depression extended into a less transmissive part of the aquifer after about 400 minutes of pumping causing a change in the graphed slope." In defense of this position, Terran (1992, page 40) states "there is geologic evidence that a boundary (e.g., change in thickness or reduction in the permeability) exists approximately 900 feet south of the pumped well."

Terran (1992) does not discuss the geologic feature that causes the aquifer transmissivity change 900 feet south of the pumping well. Presumably, the feature is linked to the Porters Creek Clay shown in Figure IV-3. Granted that some type of reduction in transmissivity could occur south of MW108, the important question is whether the change observed in the observation wells can be reproduced by a reduction in the transmissivity appropriately 900 feet south of MW108. This is the key question and can be easily investigated using an analytical solution.

Of relevance to the presumed boundary condition is an analytical model (Butler and Lui, 1991) that predicts drawdown in an aquifer consisting of infinitely linear strips with constant values of storage and transmissivity in each zone. Using this analytical model, drawdown responses were predicted in a confined aquifer infinite in extent with a uniform storage coefficient and with a four order-of-magnitude decrease in the transmissivity at a horizontal distance approximately 1,000 feet from the pumping well.

Based on an analysis of the early-time drawdown data (Terran, 1992), the storage coefficient was 0.005 and the transmissivity near the pumping well was 55,000 ft²/day. At a distance of 1,000 feet from the well, the aquifer transmissivity was reduced to 5.5 ft²/day (Figure VII-1). Drawdown responses were predicted for observation wells at radial distances of approximately 25, 50, 100, 200, and 400 feet from the well in the direction of the boundary with a constant pumping rate of 141 gal/min.

The results of the analytical model indicate that a break in the semi-log drawdown slope depends on the location of the observation well but occurs near 200 to 400 minutes. This inflection point is consistent with the observed data. At early times, a CJSI method provides a transmissivity near 55,000 ft²/day for all of the observation wells—a result consistent with observation. At late times, however, the CJSI method provides transmissivity values near 27,000 ft²/s—a result that is twice the observed values. Additional testing has shown that further decreases in the transmissivity at the boundary and an imposed no flow boundary (using image well theory) has negligible effects on the resulting drawdown plots. Based on these results,

Figure VII-1. Drawdown plots from linear strip analytical model.

a geological boundary or a reduction in transmissivity at 900 feet can cause a break in the semi-log drawdown slope at the observed time, but it cannot cause the observed increase in the semi-log drawdown slope at the observation wells.

Another important omission by Terran (1992) is a comparison of the trends in the drawdown data from the pumping and observation wells in the RGA. By superimposing analytical well solutions, the geological boundary can be shown to affect the drawdown curves at both pumping and observation wells. The slope changes observed in the observation wells should be evident in the pumping well. Comparison of Figure VI-1 and Appendix C shows that this does not occur in the MW108 pumping test. Appendix A provides appreciable data from a fluvial aquifer that clearly shows a geological boundary and the similar impacts it has on slope changes in the drawdown data from pumping and observation wells.

VII-2 Importance of Observation Well Locations

In analyzing the drawdown data obtained from the RGA, a problem is encountered in the use of solutions based on homogeneous aquifers to analyze the drawdown responses of a heterogeneous aquifer. Without a good conceptual model of the aquifer's structure, uncertainty accompanies the interpretation of any non-Theissian drawdown response. This occurs because different types of aquifer heterogeneity can produce similar types of aquifer drawdown responses (Streltsova, 1988).

Because of its fluvial deposition, the RGA aquifer is highly heterogeneous. This heterogeneity should exist on a hierarchical scale that ranges from the dimensions of pore channels to that of subenvironments such as channels, sheet flows and point bars (Young et al., 1993). Assumptions of aquifer homogeneity and layering over distances more than several meters are not valid. Appendix A serves as a testimony to problems and misinterpretations that occur when these assumptions are applied to a fluvial aquifer without justifications. In many fluvial aquifers, no analytical solution is appropriate. Numerical simulations can be used, but applications are severely limited by the lack of sufficient three-dimensional data. Of interest to the PGDP pumping tests are the results from a numerical study by Butler (1986).

Butler (1986) performs a series of numerical simulations to rigorously determine the applicability of the Theis Equation in three-dimensional aquifers that includes variations of hydraulic conductivity with depth, angular position and radial distance. In an aquifer with a constant storage coefficient that has hydraulic conductivity variations perpendicular to flow (e.g., such as a layered K profile in Figures VI-2), a pressure change will move faster through the higher zones of hydraulic conductivity (given that storage parameters are constant). As a result, the pressure change (i.e., drawdown) induced by a pumping well will not travel at a uniform rate outward in a heterogeneous aquifer. Differential pressure heads in the aquifer zones create hydraulic gradients that cause crossflow among the zones. Crossflow will be from low to high permeability zones near the well. The reliability of the transmissivity values derived from pump/test analyses

depends on whether or not crossflow among the different aquifer materials has occurred long enough to produce equilibration within the pressure field.

Butler (1986) shows that the location of the monitoring wells with respect to aquifer heterogeneity affects the reliability of early-time drawdown behavior. If the observation well is screened in a relatively low permeability area or layer, then it will not reflect the average aquifer properties until late times. In particular, for two wells located at the same radial distance from the pumping well, an observation well screened in a low permeable layer will have a greater semi-log drawdown slope than an observation well screened in a layer of higher transmissivity at early times. At late times, defined when crossflow has equalized the angular and vertical pressure differences, the two observation wells will have the same semi-log drawdown slopes. Understanding this relationship, one can deduce that at early times the semi-log slope of the drawdown data will lead to a high estimate of transmissivity, at intermediate times the semi-log slope of the drawdown data will increase because of crossflow, and at late times the semi-log slope should be most reflective of the effective transmissivity of the aquifer.

The above discussion relates to changes observed at observation wells at the same radial distance located in a leaky aquifer and in an unpumped aquifer on the other side of the aquitard. Basically, at early times, the well in the unpumped aquifer has a lower semi-log slope, but at late times the two wells exhibit the same semi-log slope. In this instance, late time occurs when a negligible percentage (< 1 percent) of water released through the aquitard is from storage.

The analysis of the MW108 and PW1 pumping tests assume that the RGA is homogeneous. With respect to the conceptual aquifer model, the highly permeable sand unit near the top of the RGA is of paramount importance. A review of the elevation of the highly permeable zone with respect to screened intervals is warranted given the results of the numerical studies described above.

Based on results from the numerical studies by Butler (1986), the drawdown data from observation wells that intersect the high K sand unit should resemble a response from a leaky aquifer, and the drawdown data from the observation wells that do not intersect the high K unit should resemble a response of an unpumped aquifer above a pumped leaky aquifer. Drawdown data from observation wells that intersect the high K unit should plot as an approximately straight line on a semi-log plot if leakance is negligible. Semi-log plots of drawdown data from observation wells that do not intersect the high K unit will initially have slopes at late times that are comparable to those in the pumping well, but display lesser slopes at early times.

From Figures IV-4 and IV-5 it is evident that the screened interval of the observation wells associated with the two pumping tests have different probabilities of intersecting the high K sand unit identified by the flowmeter tests. Because of aquifer heterogeneity, the three-dimensional structure of the sand unit near the pumping well is unknown. The assumption of the sand unit extending horizontally

outward from the pumping wells is adequate to show that the screened intervals of the observation wells are more likely to intersect the high K sand unit in the PW1 than the MW108 pumping test.

Knowledge of the screened portions of the pumping and observation wells helps to explain the difference between the responses for the pumping tests at PW1 and MW108. Appendix C shows that the observation well data for the PW1 data plot as approximate straight lines. This result is consistent with the fact that all of the screened intervals of the observation wells seem to have a high probability of intersecting the high K sand unit (Figure IV-4). Appendix C shows that the observation well data for the MW108 data is best represented as a constant slope at late times preceded by a gradually increasing slope at early times. This result is consistent with the fact that Figure IV-5 shows the screened intervals of the observation wells do not intersect the high K sand unit.

VII-3 Results From Pumping Test MW79

A pump test similar to those at PW1 and MW108 was conducted at well MW79 in the C-404 area in 1989 (Terran, 1990). The pumping rate was constant at 68 gal/min for 48 hours. Seven of fourteen wells monitored during the constant rate test responded in the 48 hours. The CJSI method and Theis curve matching produced similar values in transmissivity values that ranged from 3,600 to 18,000 ft²/day. This range is considerably larger than that observed at either PW1 or MW108. In addition, unlike PW1 and MW108, the pumping test produced a set of drawdown curves that plot on a semi-log scale with very different shapes (Appendix C). Some of the plots resemble those from pumping test MW108, where a nearly constant slope is observed at late times, but a gradually increasing slope is seen at early times. Other plots resemble those from pumping test PW1 where the slope at late times is nearly equal or less than the slope at early times. Table VII-1 summarizes the calculated transmissivity values from the pumping test MW79. The results in Table VII-1 are inconclusive. Terran (1990) attributed the problems with the large range in the calculated transmissivities and storativities to leakage. One should note, this assumption was made in spite of the fact that: (1) the observation wells located in an unpumped aquifer above an assumed aquitard did not display any drawdown during the test; and (2) that leakage cannot explain the very different plots of drawdown at the observations wells. Based on the results of PW1 and MW108, one should also consider the fact that any leakage from the upper aquifer is not sufficient to cause problems with a CJSI or Theis analysis.

One of the most important aspects of the pump test analysis is the location of observation wells relative to a high K sand unit above the gravel RGA aquifer. Terran (1990) provides a geologic cross section through the observation well network (Figure VII-2). Observing that the potentially high K sand unit in Figure VI-1, the wells can be grouped based on the likelihood of their intersecting the high K sand unit. Wells 80, 81, and 76 appear to have the highest probability of intersecting the high K sand unit; whereas

wells 73, 78, and 92 appear to have a low probability of intersecting the high K sand unit. As shown in Appendix C, the drawdown plots for the 80-81-76 well group have drawdowns very similar to those of observation wells from the PW1 pumping test that intersect the high K sand unit. The drawdown plots for the 78-73-92 well group, however, have drawdown values similar to those of observation wells from the MW108 pumping test that intersect the high K sand unit.

TABLE VII-1. CALCULATED TRANSMISSIVITY VALUES
FROM THE MW79 PUMPING TEST (FROM TERRAN, 1990)

Well	Transmissivity (ft ² /day)	
	CJSL Method	Theis Method
68	12,670	NC
73	16,377	16,580
76	11,400	10,940
78	18,121	20,860
80	3,930	2,620
81	3,740	3,622
89	NC	NC
92	6,300	6,016

In re-examining the results from the pumping test at MW79, the wide range of calculated transmissivity values and observed drawdown plots can be explained by a proper conceptual model of the aquifer heterogeneity obtained from borehole flowmeter tests and inferred from pumping tests PW1 and MW108. Although not mentioned by Terran (1990), the results from MW79 further illustrates the potential importance of aquifer heterogeneity to pumping test analyses and the possible misinterpretation of drawdown data when homogeneity is assumed in a heterogeneous aquifer.

NOTE: The above section is based on one possible interpretation of available drilling logs.

NOTE: The above sections are based on one possible interpretation of available drilling logs.

Generalized Lithology in the C-404 Area

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Figure VII-2. Well location and geological cross section for MW79 pumping test.

CHAPTER VIII

SUMMARY

Multi-well pumping tests have been conducted at well MW79, MW108, and PW1 at PGDP to determine the hydraulic properties of the RGA. Previous analyses of these pumping tests have assumed the RGA to be relatively homogeneous. To evaluate the applicability of his assumption, TVA personnel performed borehole flowmeter tests at wells MW108 and PW1. For ambient flow conditions, the flowmeter results indicated upward flow. For pumping conditions, the flowmeter results identified a 2- to 3-foot highly permeable sand layer at the top of the RGA.

The high K sand unit is attributed to meandering river deposits and appears to exist at all three pumping well locations based on available geologic data. The "high K sand" may be 10 times more permeable than the gravelly portion of the RGA. Hydraulic conductivity estimates for this sand unit range from 1,000 to 7,000 ft/day, but these estimates are probably high because of problems associated with sand packs that extend above the well screens near the high K layer. The identification of a large contrast in the vertical profile of hydraulic conductivity in the RGA implies that problems exist with the analyses of the three multi-well pumping tests conducted at PGDP. As a result, it is prudent to re-examine the previous analyses with the knowledge that vertical, and perhaps horizontal variations in hydraulic conductivity values are significant. For the purpose of this report, the re-evaluation is limited to the calculated transmissivity values.

The analysis of pumping test MW79 (Terran, 1990) led to wide range in the calculated transmissivity values and trends in the semi-log drawdown plots. The large variability in the transmissivity values and drawdown plots was attributed to leakance, although there was no basis for the assumption based on drawdown data in an overlying aquifer. The analysis of pumping test PW1 (CH2M Hill, 1990) provided a consistent set of drawdown plots and transmissivity values. For the PW1 pumping test, the CJSI method and Theis curve matching were considered applicable—a position contrary to the conclusion of the MW79 pumping test. The analysis of pumping test MW108 (Terran, 1992) provided a consistent set of semi-log drawdown plots; but these curves were very different from those from the PW1 test. Significant variability exists for transmissivity values calculated at early and at late times. This difference reflects a slope change in the semi-log drawdown plots near 400 minutes. To explain the slope change, a change in transmissivity with distance was assumed, but further evaluation suggests that the assumption is not justified.

The results and implications provided by trends in the drawdown plots and the calculated transmissivity values from the three pumping tests cannot be easily integrated. As discussed throughout the report, a major problem with the original interpretations of the three pumping tests is the assumption that the RGA is uniformly homogeneous. An extensive literature review by Young et al. (1993) clearly illustrates the complex spatial variability observed in most fluvial aquifers. The geologic data suggests that

even on an elementary level of inhomogeneity, the RGA aquifer can be subdivided into a lower sandy gravel zone and an upper zone of well sorted sand.

In re-evaluating the pumping tests, an important issue is the location of the observation well with respect to the high K sand unit. For all three pumping tests, the pressure change in the pumping well is most quickly distributed into the high K sand unit. The resulting non-uniform pressure distribution in the RGA creates hydraulic gradients perpendicular to the groundwater flow toward the well. As the pumping test continues, the resulting crossflow equilibrates the pressure distribution between the upper and lower portions of the RGA. As a result, the semi-log slope of the drawdown curves of wells that intersect and do not intersect the high K sand unit can have very different slopes at early times but similar slopes at late times. Observation wells that intersect the high K sand unit should have semi-log drawdown plots with slopes at late times less than or equal to slopes at early times (decrease in slope occurs as leakance occurs). Observation wells that do not intersect the high K sand unit should have semi-log drawdown plots with nearly constant slopes at late times preceded by increasing slopes at early times. At sufficiently late times, the slopes of observations wells at the same radial distance but screened in different vertical locations in the RGA should have similar slopes.

Given the location of the high K layer in the RGA and the importance of crossflow in heterogeneous aquifers, the results from the three pumping tests can be easily integrated into a more holistic conceptual model of the RGA. The wide range of drawdown responses for pumping test MW79 occurred because some of the observation wells intersected the high K sand unit but other observation wells did not. The drawdown responses for pumping test PW1 resemble those for a confined aquifer because all of the observation wells intersected the high K sand unit. The drawdown responses for pumping test MW108 appear to be affected by a geological boundary because all of the observation wells do not intersect the high K sand unit. Because aquifer heterogeneity has been ignored in all previous pumping test analyses, their conclusions should be considered inexact.

CHAPTER IX

RECOMMENDATIONS FOR FUTURE WORK

Based on the geologic and K data in this report, the correlation between a sandy facies near the top of the RGA and the high K values is very likely. As result, bulk hydraulic parameters, such as the average K calculated from previous aquifer tests at PW1 and MW108, will greatly underestimate the average migration rates of solutes. Furthermore, groundwater transport processes and the success of any groundwater remediation system will be greatly affected by the occurrence and interconnection of the sandy facies.

Future studies should include numerical modeling and field work. Special consideration should be given to an examination of the attributes and the continuous nature of sediment facies at the PGDP (i.e., the uppermost sand unit within the RGA). Field work should be focused on characterizing the hydraulic conductivity, dimensions, and anisotropy of the different aquifer facies. This information can be obtained with a judicious combination of soil core analyses (Boggs et al., 1990; Young and Julian, 1991), EM borehole flowmeter tests, and small-scale tracer tests (Young 1991a,b; Young, 1993c).

Additional geological data gathering and facies mapping is required to devise an adequate conceptual construct of the aquifer. The TVA Engineering Laboratory has successfully applied cone penetrometer surveys for similar surveys (Young and Julian, 1991). The cone penetrometer method is cost-effective and especially applicable to unconsolidated sediments (without large percentages of gravel) when extensive subsurface data is needed. Because of their depositional origin, fluvial aquifers are not well portrayed by stationary models (Young et al., 1993). As a result, numerous philosophical and technical problems can occur when attempting to represent the hydraulic conductivity field of a fluvial aquifer with a stationary model (Young, 1993b). Numerical modeling of the fluvial aquifer should include a non-stationary model for the hydraulic conductivity field. The reliability of any modeling approach should be verified with data sets from existing multi-well pumping tests and any future pumping and/or tracer tests.

CHAPTER X

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APPENDIX B

LIST OF FLOWMETER DATA

Paducah Gaseous Diffusion Plant

Well PW1

Depth (m)	Ambient Flow (L/min)	Pump Flow (L/min)	Net Flow (L/min)	Differential Net (L/min)	Horz. Hyd. Conductivity (cm/s)
18.3	-0.040	-18.165	18.1	—	
19.2	-0.003	-5.515	5.5	12.6	0.001529
21.9	.006	-5.904	5.9	-0.4	-0.00001
22.9	.040	-4.606	4.6	1.2	0.000153
23.8	.093	-4.244	4.3	0.3	0.000037
25.6	.101	-3.767	3.8	0.5	0.000028
26.5	.059	-3.100	3.2	0.7	0.000085
27.4	-.028	-1.231	1.2	1.9	0.000237
28.3	.013	-1.011	1.0	0.2	0.000021
29.0	.097	-.284	0.8	0.6	0.000116
29.9	.002	-.139	0.1	0.2	0.000029

Well MW108

Depth (m)	Ambient Flow (L/min)	Pump Flow (L/min)	Net Flow (L/min)	Differential Net (L/min)	Horz. Hyd. Conductivity (cm/s)
21.3	-0.013	-17.682	17.669	—	
21.9	0.100	-3.797	3.897	13.772	0.006935
22.6	0.102	-4.070	4.172	-0.275	-0.00013
23.2	0.111	-3.989	4.100	0.072	0.000036
23.8	0.128	-4.144	4.272	-0.172	-0.00008
24.4	0.135	-4.478	4.613	-0.341	-0.00017
25.0	0.149	-3.672	3.821	0.792	0.000398
25.6	0.139	-3.550	3.689	0.132	0.000066
26.2	0.147	-2.677	2.824	0.865	0.000435
26.8	0.072	-2.029	2.101	0.723	0.000364
27.4	-0.041	-1.409	1.368	0.733	0.000369
28.0	0.162	-0.590	0.752	0.616	0.000310
28.7	0.203	-0.393	0.596	0.156	0.000078
29.3	0.148	-0.365	0.513	0.083	0.000041
29.6	-0.009	-0.124	0.115	0.398	0.000400
30.2	-0.007	-0.122	0.115	0	0.000000

Table3.Drw

APPENDIX C

SEMI-LOG DRAWDOWN PLOTS FROM MW108, PW1, AND MW79 PUMPING TESTS

PZ114 Corrected Drawdown with BE = 55%

PZ107 Corrected Drawdown with BE = 70%

PZ110 Corrected Drawdown with BE = 78%

PZ117 Corrected Drawdown with BE = 85%

PZ109 Corrected Drawdown with BE = 87%

PZ118 Corrected Drawdown with BE = 100%

MW108 PUMPING TEST

PW1 PUMPING TEST

SEMILOG DRAWDOWN CURVES CORRECTED FOR BAROMETRIC

MW79 PUMPING TEST