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**An Evaluation of a Borehole Induction Single-Well Tracer
Test to Characterize the Distribution of Hydraulic
Properties in an Alluvial Aquifer**

by

Terrance J. Huettl

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ABSTRACT

In order to assess the potential of a borehole induction single-well tracer test for the characterization of the distribution of hydraulic properties in an alluvial aquifer, a series of tracer tests were performed at a field site in the Kansas River alluvium. The test procedure involved the injection of a nonreactive, electrically conductive tracer into a well under artificially induced, steady-state flow conditions. Vertical variations in the rate of the horizontal invasion of the injected tracer solution are computed from repeated logs using a focussed induction borehole probe. These data were then employed to construct vertical profiles of effective porosity and hydraulic conductivity at the injection well.

The results from the initial group of tracer tests did not agree with results from previous studies at the site. Further experimentation showed that air, entering the aquifer during tracer injection, altered hydraulic and electrical properties of the formation during the tests. This experimentation also revealed that differential aquifer and well head losses caused vertical head variations in the injection well during tracer injection. This head variation produced differential tracer invasion rates that were not simply a function of the hydraulic properties. It was also suspected that a drilling-induced disturbed zone adjacent to the wells may have influenced the rate of tracer invasion during the early portion of the tests.

In order to prevent the introduction of air into the aquifer and eliminate the vertical head variations during tracer injection, a drop pipe was constructed to house the injection solution during its descent into the injection well and to evenly distribute the tracer within the screened interval. The method of data analysis was also modified to remove the influence of a drilling-induced disturbed zone on the estimation of hydraulic conductivity. A repeated tracer test was then conducted using the new procedures. The results of the repeated test are reasonable, considering the nature of the aquifer material and results of previous studies from the same well. Using the modified procedures, it appears that the borehole induction tracer test method has potential for accurate characterization of alluvial aquifers.

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CHAPTER 1 INTRODUCTION

1.1 Background

In order to predict the movement of water and pollutants accurately in the subsurface, it is necessary to understand the factors controlling their transport. Spatial variability in aquifer hydraulic parameters greatly influences the movement of groundwater and contaminants (Freeze and Cherry, 1979). Therefore, accurate characterization of parameter spatial variability is very important if reliable predictions of contaminant transport are to be made.

Taylor *et al.* (1990) recently evaluated commonly employed methods for estimating spatially varying hydraulic properties in unconsolidated geologic formations. They concluded that, owing to near-hole drilling disturbances, inadequate sediment sampling techniques, and sampling bias, current methods have significant limitations. Clearly, refinement of current methods or the development of new methods is needed if hydrogeologists are to keep pace with increasing demands for sophisticated and accurate predictive techniques.

The borehole induction single-well tracer test is a new method of aquifer characterization apparently first reported in the groundwater literature by Taylor and Molz (1990). The method provides estimates of vertical

variations in hydraulic properties at a scale that has been difficult to obtain in the past. Detailed information of this kind can greatly improve understanding of the primary controls on subsurface groundwater flow and contaminant transport at a site.

To date, there have been no published evaluations of the borehole induction single-well tracer test method. Although the study of Taylor and Molz (1990) produced reasonable results, a thorough evaluation of the method is needed in order to assess the applicability of the method in other geologic settings. In the following chapters, the tracer test method and its application at a research site of the Kansas Geological Survey will be described. The first three chapters summarize the Taylor and Molz (1990) method and its application for four tests conducted in an alluvial aquifer. Chapter 4 discusses problems encountered during the first four tests and important refinements necessary for field application of the method. Chapter 5 summarizes a fifth test conducted with the refined field procedure along with refinements made to the Taylor and Molz (1990) tracer test data analysis method. The final chapter evaluates the viability of the tracer test method.

1.2 Field Site

Five tracer tests were conducted at the Geohydrologic Experimental

and Monitoring Site (GEMS), located three miles northeast of Lawrence, Kansas, on land owned by the University of Kansas Endowment Association (Figure 1.1). The bedrock beneath GEMS is a silty sandstone of the Pennsylvanian Douglas Group (Davis and Carlson, 1952). The bedrock at the site is covered by approximately 22 m of unconsolidated Kansas River alluvium of the early Wisconsinan Newman terrace (Davis and Carlson, 1952). The alluvium is composed of approximately 11 m of sand and gravel overlain by 11 m of silt and clay. The sand and gravel unit, the focus of this study, is composed primarily of quartz, feldspar, and chert grains and contains an average of 2 to 3 weight percent silt and clay (McElwee *et al.*, 1993). Cores from this unit display cross-bedding, variable grain size and clay content, and clay drapes, which measure approximately 1 to 3 cm in thickness. The average phi size, average repacked core hydraulic conductivity, and average undisturbed core total porosity determined from core material from several wells are 0.06, 48 m/day, and 0.28, respectively (McElwee *et al.*, 1993).

The underlying Pennsylvanian bedrock and the overlying silt and clay unit hydraulically restrict groundwater flow in the sand and gravel, forming a leaky confined aquifer. Water levels in the sand and gravel and the silt and clay intervals are roughly 3 m and 2 m from the land surface, respectively. Limited data indicate that the lateral hydraulic gradient in the confined

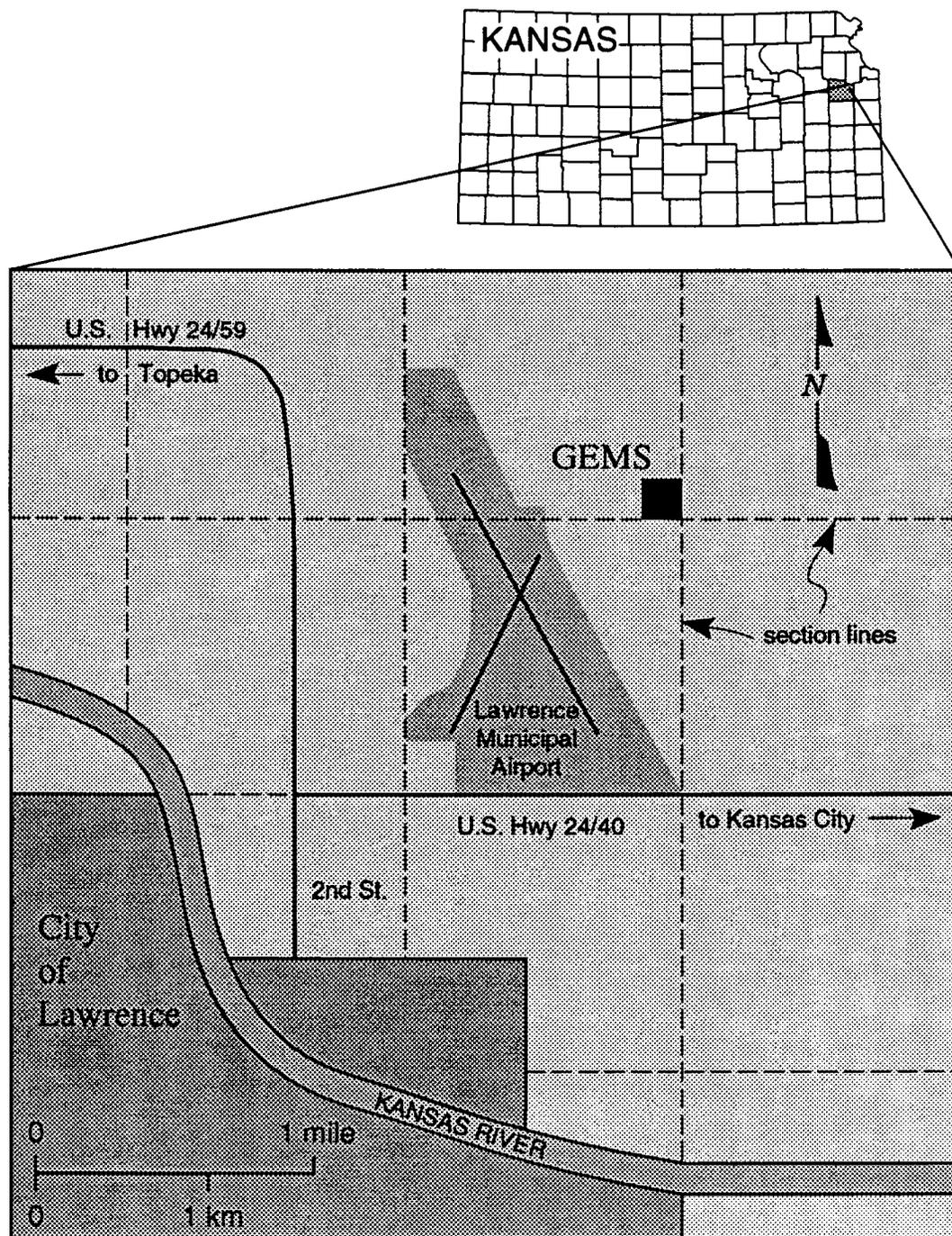


Figure 1.1 Location of GEMS.

aquifer ranges from approximately 2×10^{-3} to 4×10^{-3} throughout the year and is directed S20°E. The four injection wells used for the five tests (Figure 1.2) are constructed of 0.051 m diameter PVC pipe and are fully screened across the sand and gravel unit.

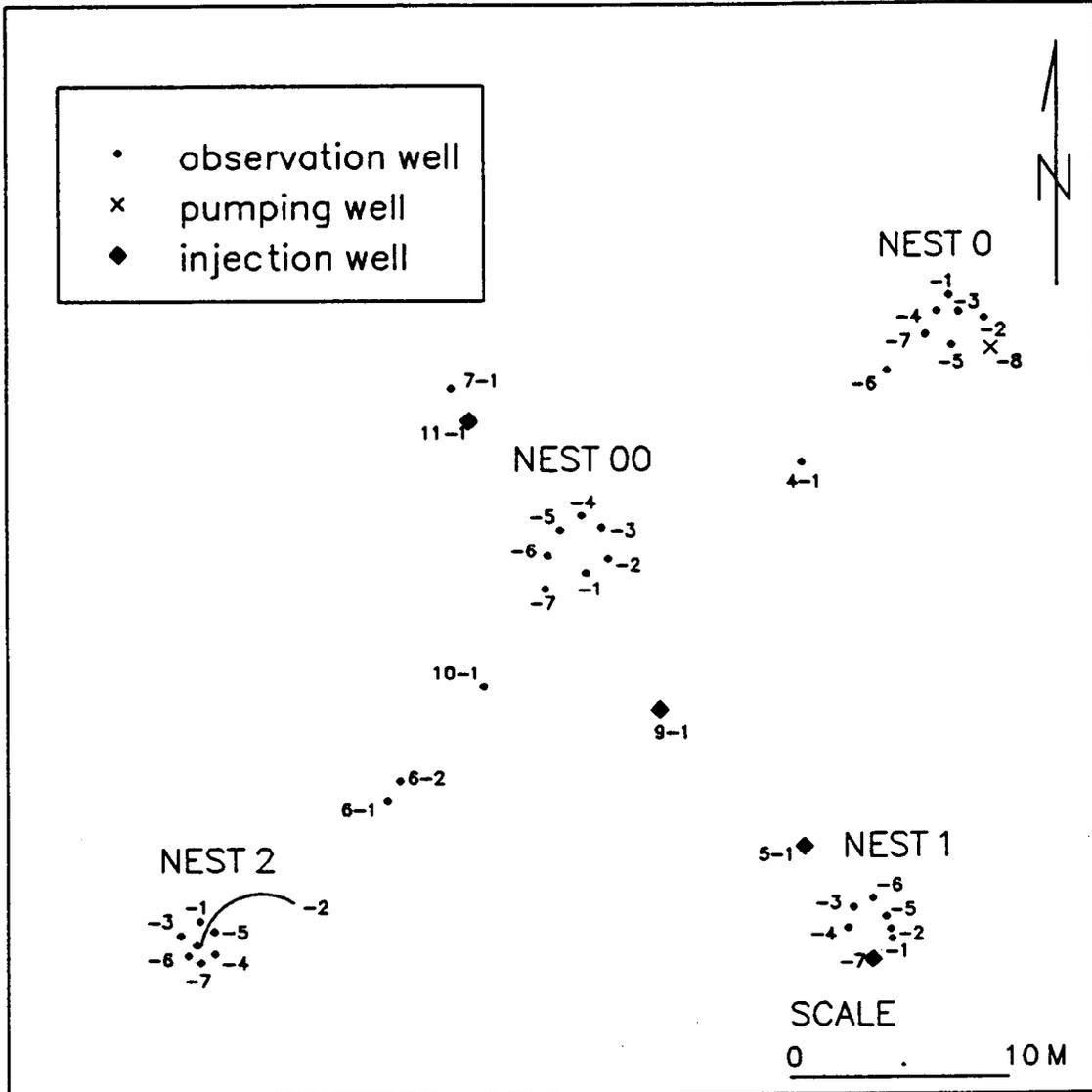


Figure 1.2 Location of wells at GEMS.

CHAPTER 2 TRACER TEST METHODOLOGY

2.1 Summary of Method

The Taylor and Molz (1990) tracer test method involves the injection of a nonreactive, electrically conductive tracer solution into a well under artificially induced, steady-state flow conditions (Figure 2.1). As the tracer solution enters the aquifer through the well screen, it moves radially outward, displacing the native pore fluid. Since the electrical conductivity of a formation is significantly controlled by the porosity and pore fluid chemistry (Dobrin and Savit, 1988), a considerable increase in the formation conductivity occurs as the tracer advances radially outward from the well. The invasion of the tracer is monitored by repeated surveys using a focussed induction borehole probe. The rate of invasion as a function of depth is determined from the induction logs. Detailed vertical profiles of the effective porosity and the horizontal component of hydraulic conductivity are constructed using the tracer invasion rates, the induced hydraulic gradient, and the observed change in formation electrical conductivity as the tracer solution invades the aquifer.

2.2 Tracer Injection

Induced steady-state flow conditions were produced in the injection

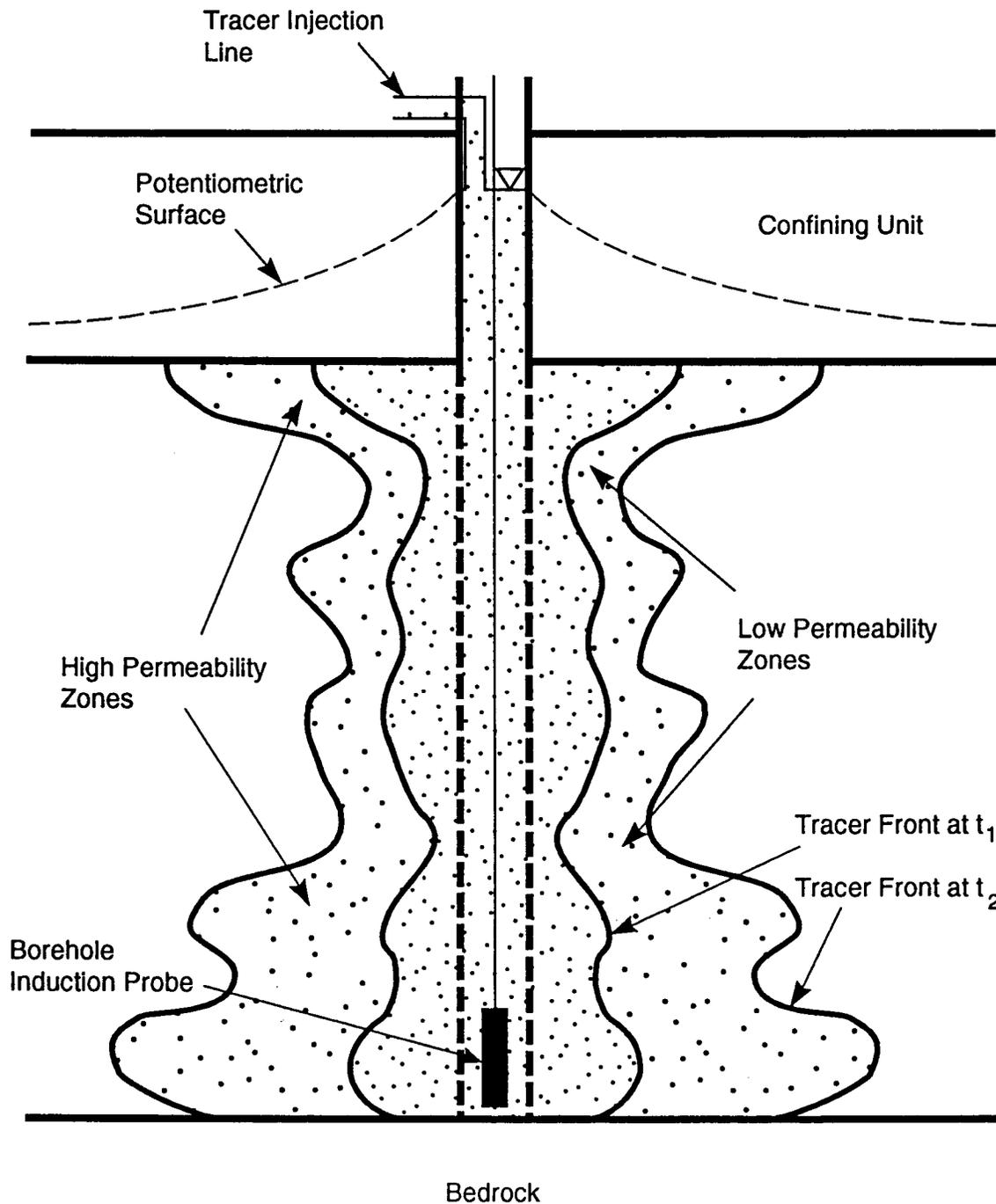


Figure 2.1 Illustration of single-well tracer test (modified from Huettl *et al.*, 1993).

well prior to the introduction of the tracer solution. This was accomplished by pumping native GEMS groundwater from a 0.102 m diameter PVC cased well (0-8 in Figure 1.2) screened in the sand and gravel aquifer using a 0.089 m diameter submersible pump (*Simer* model 9BC), and directly discharging it into the injection well. For each test, the pumping well was located far enough from the injection well (> 20 m) that drawdown at the injection well due to pumping was negligible. (A practice withdrawal test conducted at a discharge rate of 61 L/min. (16 gal./min.) produced drawdown of 0.70 m in the pumping well and only 0.06 m at a fully penetrating observation well located 2.0 m from the pumping well.) A constant injection rate of 53 - 61 L/min. (14 - 16 gal./min.) was used to induce a head of 3 - 4 m in the injection well during the first four tests. When the water level in the injection well stabilized, flow within the volume of the aquifer adjacent to the well was assumed to be at steady state.

Once steady-state flow conditions were achieved, a concentrated saline solution was pumped from a storage tank directly into the water line connecting the pumping and injection wells. The tracer solution, which consisted of water from the pumping well and the concentrated saline solution, discharged into the injection well at the land surface, cascaded down the well, and entered the aquifer through the well screen. The tracer replaced the native pore fluid as it was transported radially outward under

the induced hydraulic gradient. As the tracer advanced, the conductivity of the formation increased. This change was monitored throughout the test with repeated surveys using a borehole induction tool.

Tracer injection continued until the tracer had traveled a radial distance of roughly 2.5 m from the well (the approximate radial detection limit of the induction tool). During this time, 21,600 - 29,200 L (5700 - 7700 gal.) of tracer solution were injected into the aquifer. The exact volume depended on the porosity of the media and the length of the screened interval. The four injection periods lasted 5.5 to 8.1 hours.

2.3 Tracer Solution

A dilute NaCl solution was used for the tracer due to the high solubility, relative inertness, low cost, and low toxicity of NaCl. The specific conductivity of the tracer solution (115 - 200 mS/m) was roughly 2 to 3 times the specific conductivity of the native groundwater (64.5 mS/m). During each of the four tests, approximately 7 - 20 kg of NaCl was pumped into the aquifer.

The saline solution was prepared and stored in a 1988 L (525 gal.) polyolefin storage tank. GEMS native groundwater, used as the solvent, was pumped into the tank prior to injection. To ensure complete dissolution of the solute and thorough mixing throughout the test, a small submersible

pump (*Little Giant* model 2E) was used to continuously circulate the solution. (Note that the electrical conductivity of the saline solution was not monitored during the tests because the conductivity of the solution exceeded the measurement capacity of our field conductivity probe. However, it is recommended that the solution be periodically sampled and that the electrical conductivity be measured after diluting the sample. This procedure will ensure that complete dissolution and thorough mixing has occurred throughout the test.) A second submersible pump (*Grundfos* model MP1) was used to pump the concentrated saline solution from the tank into the main injection line.

2.4 Induction logging

The electrical conductivity of the formation adjacent to the injection well was measured before, during, and after each tracer test with a focussed induction borehole probe manufactured by *Century Geophysical Corporation* (model 9510). The borehole probe contains a pair of transmitter coils carrying an alternating electric current. This current produces an alternating magnetic field in the formation surrounding the tool. The magnetic field induces current loops in the formation outside the well. This current creates a magnetic field that induces an electric current in a pair of receiver coils inside the induction probe. The magnitude of the current in

the receiver coils is a function of the initial current in the transmitter coils and the ability of the formation to conduct the current loops. As the electrically conductive tracer solution invades the formation, the ability of the formation to conduct an electric current increases. The borehole induction tool measures this change and permits the determination of the position of the tracer front with respect to the injection well.

During the tracer tests, the conductivity of the formation was measured at 0.030 m intervals as the induction tool was slowly raised in the injection well. The conductivity readings (units of mS/m) were transmitted in digital form to the land surface and stored in a computer.

The injection well was logged with the induction probe four times prior to the initiation of tracer injection. (Pretest experiments showed that statistical variability (noise) in conductivity values is reduced by computing average logs from repeated measurements. The number four was chosen for the number of repeat logs as a compromise between logging time and variability reduction in log values.) Following the initiation of tracer injection, the injection well was initially logged every 20-35 minutes to monitor the radial invasion of the tracer solution into the aquifer. Logging continued at increasing time intervals until the tracer solution approached the radial detection limit of the induction probe. This state was assumed to have been reached when the conductivity logs showed little change with continued

injection. At this time the injection well was logged four more times and tracer injection was terminated.

2.5 Test Monitoring

During practice injection tests and the first tracer test, pressure transducers (*Instrumentation Northwest* models PS-7000 and PS-9000) were placed in the pumping, injection, and observation wells to monitor water levels. These data were recorded using data acquisition equipment consisting of a 16-bit data acquisition board (*Iotech* model ADC488/16) placed in a 286-12 Mhz IBM-compatible personal computer (*Zenith* model ZW-241-82) and appropriate software (*Scentech* Turbolab 1.0). These data were used to determine the induced hydraulic gradient in the vicinity of the injection well. Pressure transducers were not used for subsequent tracer tests due to the lack of sufficiently close observation wells and the potential for damage to the pressure transducer in the injection well as a result of shock from the impact of the cascading water. For these tests, the water level in the injection well was monitored with an electric water level tape (*Solinst*).

A flow meter (*Omega* model FP-5800) attached to a 0.025 m inner diameter PVC flow-through pipe fitting monitored the tracer solution injection rate. The meter was inserted into the main injection line downstream of the

point of injection of the concentrated saline solution. The meter was monitored with the data acquisition equipment or by visual inspection.

A fluid conductivity cell (*Hach* model 44600) monitored the electrical conductivity of the tracer solution in the injection line. This meter also served as a check to ensure that all pumps were operating properly. A second conductivity cell (*Solomat* Chemistry Module 4007) was used to detect the appearance of the tracer solution at the bottom of the screened interval of the injection well in three of the initial four tests. During two tests, the tracer solution reached the bottom of the well within three minutes of the start of tracer injection. The tracer solution reached the bottom of the well during the third test within 10 minutes.

2.6 Remediation

Following the completion of each test, the injection well was pumped to remove the tracer from the aquifer. The injection well was pumped using an air-lift system (air compressor: *Curtis* model ES-20) at approximately twice the tracer injection rate. Pumping from the injection well continued until 1.5 - 3.1 pore volumes (one pore volume is defined here as a volume equivalent to the volume of tracer solution injected) were removed. During this time, the specific conductivity of the discharge returned to the pretest level. The water pumped out during remediation was transported off site (>

50 m) using irrigation pipe and discharged onto the land surface. Most of the discharge contained Cl⁻ levels below EPA specified drinking water standards and posed essentially no threat to the natural environment. The tracer was removed primarily because of potential interference with future tests at the site.

During tracer removal the specific conductivity of the discharge was periodically measured at the surface. An approximate mass balance (comparison of tracer injected to tracer removed) showed that only 20 to 35 percent of the tracer was removed. Repeated formation conductivity logs suggested that some of the tracer was still present near the injection well following remedial pumping. Further pumping, however, removed no additional detectable tracer. It is suspected that during tracer injection a significant volume of tracer solution moved preferentially in some intervals, traveling beyond the influence of remedial pumping.

CHAPTER 3 THEORY OF TRACER TEST DATA ANALYSIS

3.1 Porosity Estimation

It has been shown experimentally that a relationship exists between formation electrical conductivity, native pore water electrical conductivity, and porosity (Archie, 1942). This relation, known as Archie's Law, is found in most geophysical logging texts (e.g., Bateman, 1985; Dewan, 1983; Ellis, 1987; Schlumberger, 1989). The Taylor and Molz (1990) tracer test method employs this relationship to construct a model of formation conductivity that is used to estimate effective porosity for each sample interval from the induction logs.

The Taylor and Molz (1990) model defines the electrical conductivity of the formation (σ_{fm}) as a sum of a contribution from the matrix (σ_m) and that from the pore fluid (σ_{pf}):

$$\sigma_{fm} = \sigma_m + \sigma_{pf} \quad (1)$$

The contribution from the pore fluid can be represented by Archie's Law:

$$\sigma_{pf} = (\sigma_f \theta^m) / \alpha \quad (2)$$

where σ_f = electrical conductivity of the pore fluid, θ = porosity, m =

cementation factor, and α = tortuosity.

Substituting Archie's Law into Equation 1 yields:

$$\sigma_{fm} = \sigma_m + (\sigma_f \theta^m) / \alpha \quad (3)$$

From the induction logs taken before tracer injection and those taken after the tracer moves beyond the radial detection of the tool (henceforth termed tracer saturation), the formation conductivity is known when the aquifer is saturated with pore fluid of two different electrical conductivities.

Equation 3 can therefore be written as 2 equations:

$$\sigma_{fm1} = \sigma_m + (\sigma_{f1} \theta^m) / \alpha \quad (4)$$

$$\sigma_{fm2} = \sigma_m + (\sigma_{f2} \theta^m) / \alpha \quad (5)$$

where σ_{fm1} and σ_{fm2} are the formation conductivity before tracer injection and after tracer saturation, respectively, and σ_{f1} and σ_{f2} are the conductivity of the native pore water and the tracer solution, respectively. Subtracting Equation 4 from 5 and solving for porosity yields:

$$\theta = \left[\frac{(\sigma_{fm2} - \sigma_{fm1}) \alpha}{(\sigma_{f2} - \sigma_{f1})} \right]^{1/m} \quad (6)$$

Note that θ is dependant on the change in formation conductivity ($\sigma_{fm2} - \sigma_{fm1}$) that occurs when the native pore water (σ_{f1}) is replaced by the

tracer solution (σ_{f2}). Since only interconnected pore spaces will fill with the tracer solution, θ represents the effective porosity (interconnected pore volume / total sample volume) of the formation.

The cementation factor (m) and tortuosity (α) are empirical factors dependant on lithology and pore structure. It has been shown that for unconsolidated sands these variables are approximately 1.4 and 1.0, respectively (Jackson *et al.*, 1978).

3.2 Radius of Tracer Invasion

The radius of tracer invasion is determined for each interval of an induction log using the radial dependence relationship for the induction probe. The formation conductivity measured for a single interval is a weighted average of the conductivity adjacent to that interval. The relationship between the magnitude of contribution of a specific portion of a formation and the radial distance from the probe to that portion of the formation is called the response function. Figure 3.1 displays the normalized theoretical radial response function for the probe used for this work (*Century Geophysical Corporation*, unpublished). This curve displays how the probe weights the conductivity of specific portions of the formation around the probe to determine an average formation conductivity for each interval. The shape of this curve is a function of receiver and transmitter coil

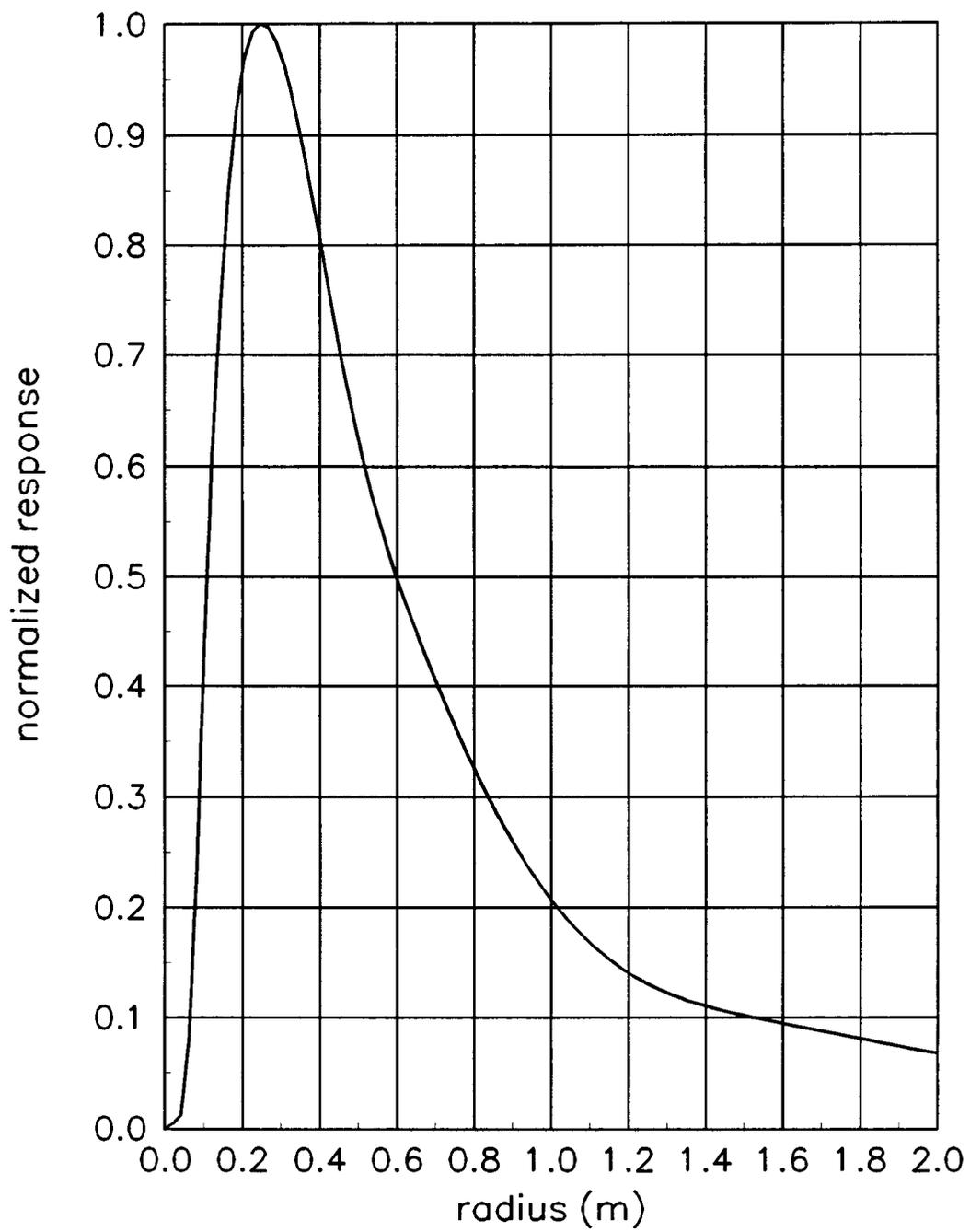


Figure 3.1 Induction probe theoretical radial response function (modified from *Century Geophysical Corporation*, unpublished).

geometry and can be theoretically determined (Saito, 1982).

Figure 3.2 is a plot of the cumulative sum of the theoretical radial responses. This function, $Z(R)$, enables changes in formation conductivity during tracer injection to be used to estimate the depth of tracer invasion. (The relationship between changes in formation conductivity and depth of solution invasion was originally developed for the determination of the depth of drilling fluid invasion during well drilling operations. A discussion of this relationship can be found in most geophysical texts, including Ellis (1987) and Schlumberger (1989).) At any particular time during tracer injection, $Z(R)$ can be calculated in the following way:

$$Z(R) = \frac{\sigma_a - \sigma_{fm1}}{\sigma_{fm2} - \sigma_{fm1}} \quad (7)$$

where σ_a is a formation electrical conductivity measured at that time. Given σ_a , σ_{fm1} , and σ_{fm2} , a value for $Z(R)$ is calculated, and Figure 3.2 is used to estimate the position of the tracer front (R) at the time of that particular induction log.

Note that the use of Equation 7 and Figure 3.2 for R estimation assumes that there is no dispersion of tracer beyond the advective front. This assumption is valid due to the short distance (approximately 2.5 m) and duration (<8.1 hr.) of transport.

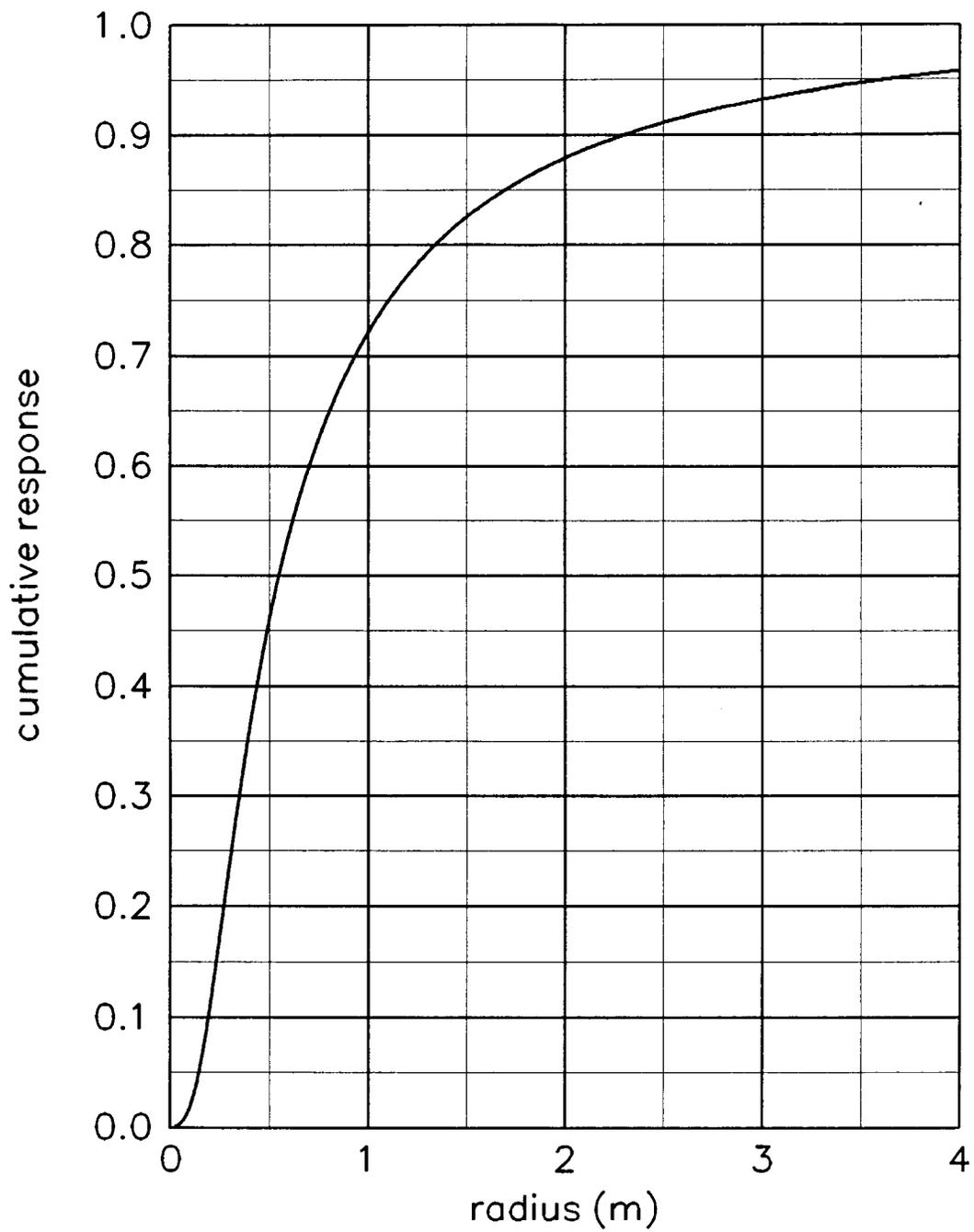


Figure 3.2 Induction probe theoretical cumulative radial response function (modified from *Century Geophysical Corporation*, unpublished).

3.3 Hydraulic Conductivity Estimation

Knowing the radial position of the tracer solution front as a function of time and the effective porosity, Taylor and Molz (1990) estimate hydraulic conductivity by equating a simple geometric representation of radial plug flow and Darcy's Law. The mobile volume of pore fluid within a vertical segment of an aquifer can be represented by a cylinder with the well at the center:

$$V = \pi R^2 b \theta \quad (8)$$

where V = volume, R = radius of cylinder, b = height of cylinder, and θ = effective porosity. The discharge into this volume can be written as:

$$Q = \pi R^2 b \theta / t \quad (9)$$

where Q = discharge, and t = time since initiation of tracer injection.

Discharge into this segment can also be written using Darcy's Law:

$$Q = -2\pi r b K (dh/dr) \quad (10)$$

where r = arbitrary radius for head evaluation (not related to R), K = hydraulic conductivity, and h = hydraulic head.

Equation 10 is a separable differential equation which can be integrated with respect to r and h :

$$\int_0^{h_w} dh = -\frac{Q}{2\pi bK} \int_{r_e}^{r_w} \frac{dr}{r} \quad (11)$$

where h_w is the induced hydraulic head (difference between static and steady-state water levels) at r_w (the radius of the injection well), and r_e is the minimum radius where the induced head is 0 m. The solution for this equation is:

$$h_w = -\frac{Q}{2\pi bK} [\ln r_w - \ln r_e] \quad (12)$$

Equation 12 reduces to:

$$Q = \frac{2\pi bKH}{\ln\left(\frac{r_e}{r_w}\right)} \quad (13)$$

where $H = h_w$.

Equating Equations 9 and 13, and solving for K yields:

$$K = \frac{R^2 \theta}{2Ht} \ln \frac{r_e}{r_w} \quad (14)$$

Given r_e/r_w , H, R (radius of tracer invasion at time t), and θ determined for each induction log sample interval (0.03 m), Equation 14 is used to estimate K for each log interval from each induction log.

CHAPTER 4 APPLICATION PROBLEMS

4.1 Data Interpretation

The results from the first four tracer tests performed in the fall of 1993 (in injection wells 1-7, 5-1, 9-1, and 11-1 in Figure 1.2) did not agree with results from previous studies at the site. Figure 4.1 contains formation electrical conductivity logs obtained before, during, and after tracer injection in well 5-1. The interval from 15.5 - 16.5 m shows little change in formation conductivity during tracer injection. This observation suggests that the permeability in this interval is very small. Permeameter and grain-size analyses of cores from this well, however, do not display a pronounced low permeability interval.

Figure 4.2 contains porosity profiles determined from the tracer test and from the analysis of undisturbed core sediment from well 5-1 (Butler *et al.*, 1994). Note the relative magnitude of the estimates determined from the two methods. The average tracer test effective porosity and core total porosity are 0.121 and 0.264, respectively. Mackay *et al.* (1986) report tracer test and core porosity estimates from an unconsolidated alluvial aquifer near Borden, Ontario. The estimates of effective and total porosity for this aquifer are 0.30 and 0.33, respectively. The ratio of effective to total porosity for GEMS and the Borden site is 0.46 and 0.90, respectively. The

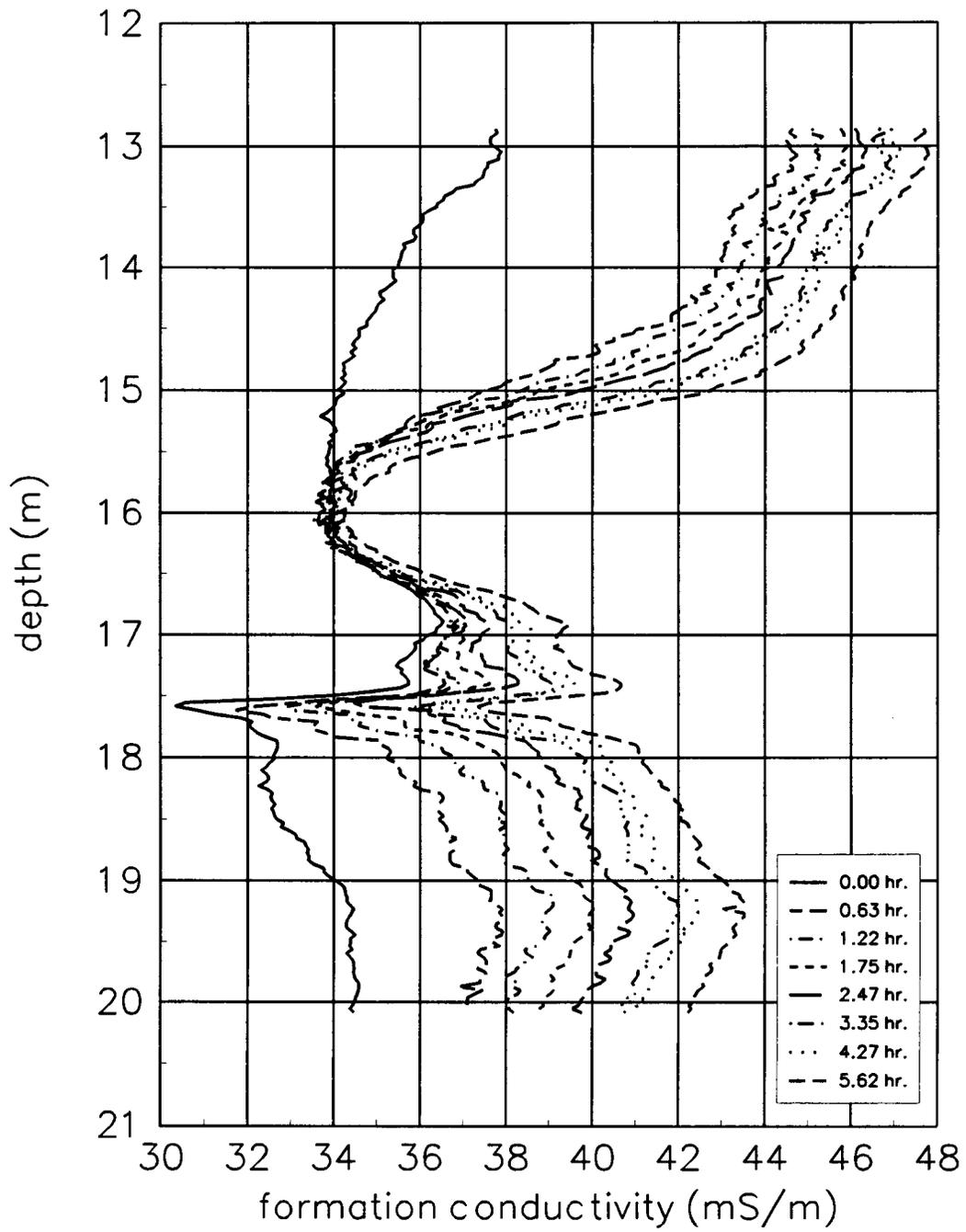


Figure 4.1 Formation conductivity before, during, and after tracer injection in well 5-1.

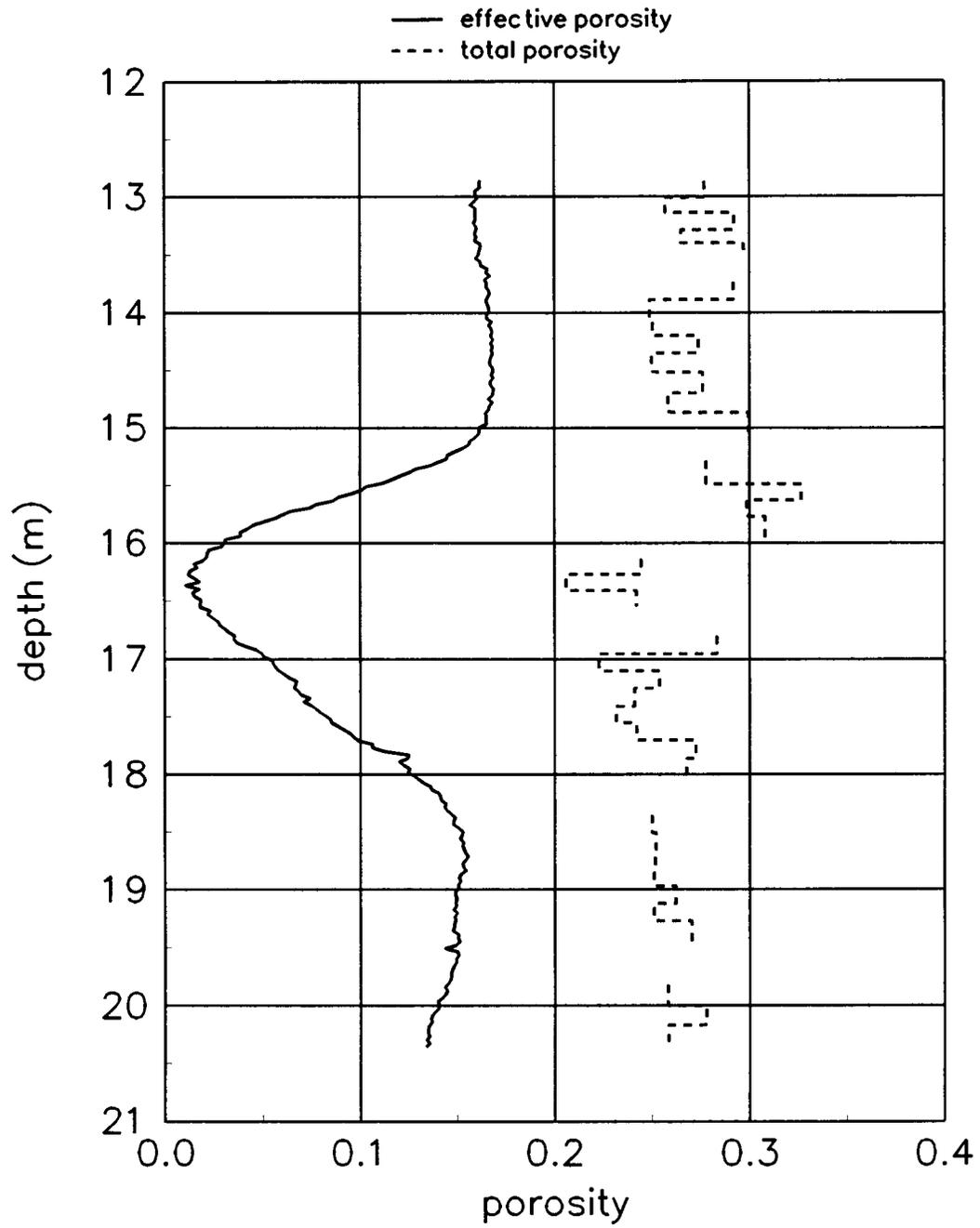


Figure 4.2 Porosity profiles from well 5-1. Total porosity from Butler *et al.* (1994).

GEMS data suggests that less than half of the pores in the aquifer are continuous. This observation seemed unlikely, considering that the aquifer is composed of unconsolidated sand and gravel. It was expected that at GEMS the effective to total porosity ratio would be closer to that observed at the Borden site.

Figure 4.3 displays hydraulic conductivity (K) profiles determined from the tracer test and from permeameter analysis of repacked core material from well 5-1 (Butler *et al.*, 1994). Again, note the relative magnitude of the estimates determined from the two methods. The average tracer test and permeameter K estimates are 2.04 and 48.2 m/day, respectively. The permeameter K represents disturbed samples because the original formation pore geometry was destroyed. The tracer test K represents groundwater movement in the same plane as the principle flow direction and in the natural undisturbed environment. Therefore, the tracer test K should be greater than the permeameter K. The fact that the average tracer test K is over an order of magnitude lower than the average permeameter K suggests that the tracer test data was in error.

All of the first four tracer tests produced similar questionable results. A simple sensitivity analysis of the tracer test model suggested that the primary controls on the parameter estimates were the induced hydraulic gradient, rate of tracer advance, and observations from the induction probe.

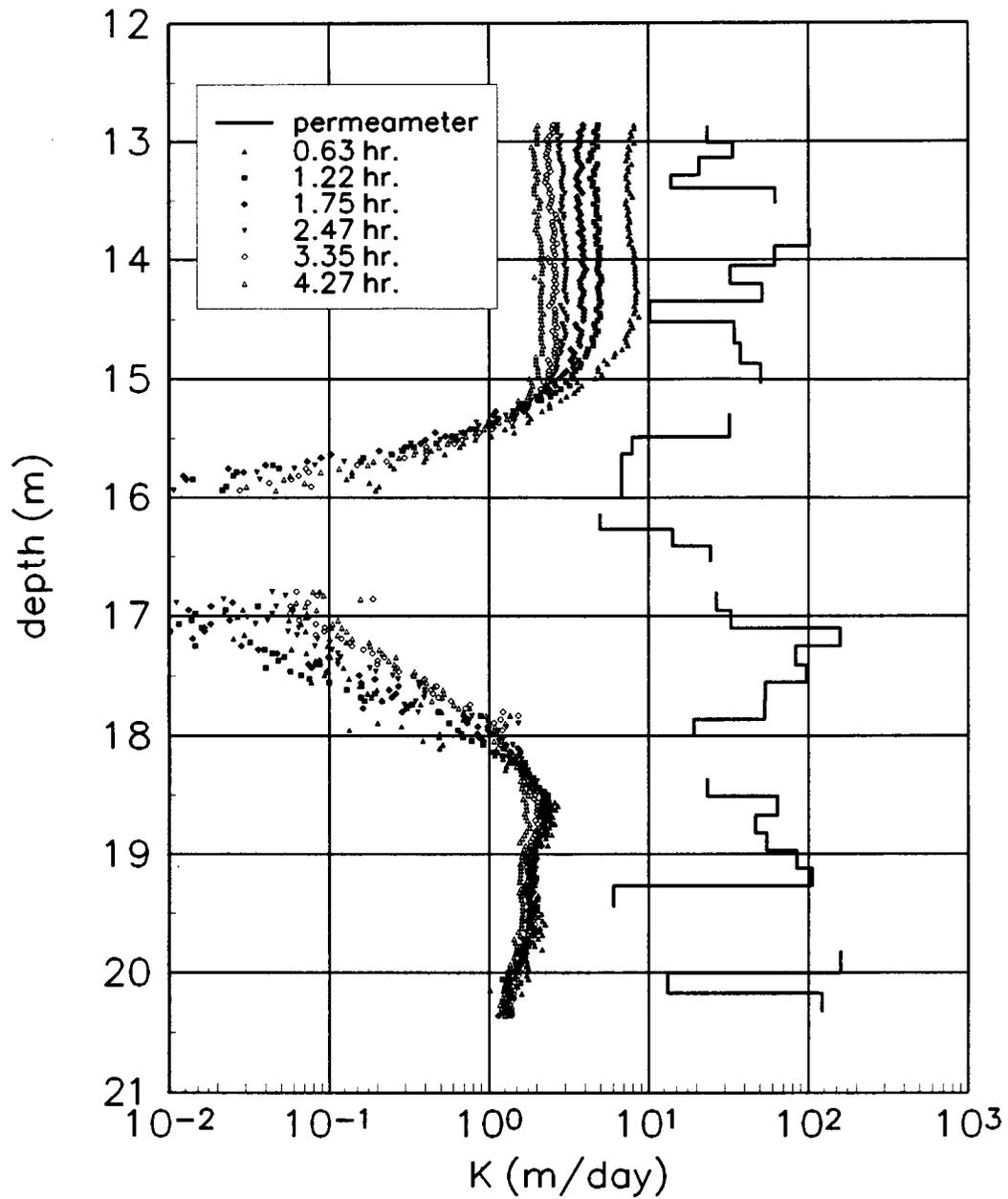


Figure 4.3 Hydraulic conductivity profiles from well 5-1. Permeameter data from Butler *et al.* (1994).

These factors were studied to determine how they were contributing to the consistent underestimation of the hydraulic parameters.

4.2 Tracer Solution Aeration

The tracer solution discharged into the injection well at land surface and cascaded down the well. It was hypothesized that during this descent, air bubbles entrapped in the turbulent column of water moved into the aquifer with the injected water. Once in the aquifer, the bubbles could clog pores, reducing the hydraulic conductivity of the near-well material and, therefore, increasing the induced hydraulic head in the injection well.

Field experiments were conducted to determine if air was introduced into the aquifer during tracer injection. In order to minimize air entrapment, a drop pipe (0.032 m ID) was placed inside the well (0.051 m ID). Water was pumped to the injection well, where it entered the drop pipe. The pipe housed the injected water during its descent in the well. The water discharged from the drop pipe approximately 2.4 m below the static water level in the well. The drop pipe was completely filled with water during injection, thereby eliminating contact between the injected water and the atmosphere.

Injection tests were performed with and without the drop pipe in order to assess if there was a difference in the induced head produced by the two

approaches. Water was pumped from well 0-8 using a 0.089 m diameter submersible pump (*Simer* model 9BC). The water entered injection well 1-7 at a constant rate of approximately 51 L/min. (13.6 gal./min.) for both tests. Pressure transducers, positioned 6.7 m below the static water level, were used to monitor the induced head. Figure 4.4 is a plot of the induced head versus time in injection well 1-7 for the two approaches. This plot displays greater induced head during the test without the drop pipe, suggesting air entered the aquifer and reduced the hydraulic conductivity of the near-well formation. Note that the induced head observed during these tests is considerably lower than the induced head observed during the first four tracer tests (Section 2.2). This phenomenon will be discussed in Section 4.3.

The possible presence of air in the formation presents a serious problem for this tracer test method. The air clogs pores, altering the hydraulic properties that are the subject of the investigation. The problem is exacerbated because the presence of gas reduces the formation conductivity measured during tracer injection (air is less conductive than the saline tracer solution). This decrease in formation conductivity alters the relationship between the induction readings and the hydraulic properties. As a result of these experiments, it was concluded that an injection drop pipe must be used during tracer injection in order to eliminate aeration of

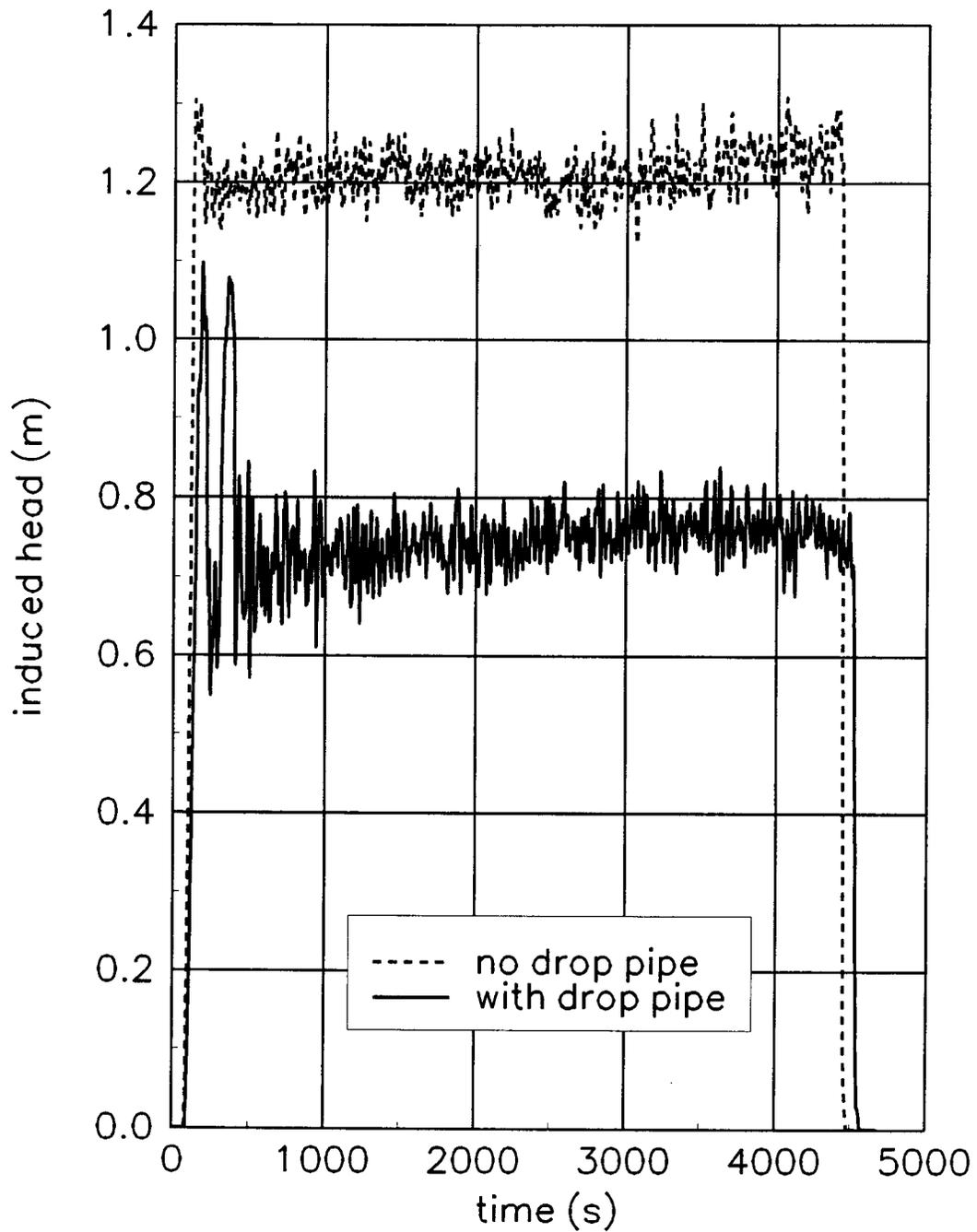


Figure 4.4 Induced head versus time in well 1-7 with and without injection drop pipe ($Q = 51 \text{ L/min}$).

the injection solution and subsequent introduction of gas into the aquifer.

4.3 Aquifer and Well Head Losses

In addition to tracer aeration, head losses also contributed to the large induced heads observed during the first series of tracer tests. Head changes in an injection or pumping well result from phenomena in both the aquifer and well (Kruseman and de Ridder, 1990). Aquifer head losses result from gradient-induced laminar flow. They are time-dependant and linearly proportional to discharge. Well head losses consist of both linear and non-linear components. Linear well losses result from well installation disturbances (skin) and friction in the well casing and screen. Non-linear well losses result from turbulent flow in the well screen, casing, and aquifer near the screen.

Field experiments were performed to assess aquifer and well head losses during injection. Water was pumped from well 0-8 using a 0.089 m diameter submersible pump (*Grundfos* model SP 2-12). The water was discharged at 57 L/min. (15 gal./min.) into well 5-1 via the injection drop pipe. The discharge end of the drop pipe was 0.070 m above the static water level. Following the initiation of injection, the discharge end of the drop pipe was continuously below the water level in the well. Two pressure transducers, placed at the bottom of the well and above the screen,

respectively, monitored changes in head during injection. Once steady-state flow conditions were achieved, the lower pressure transducer was raised at 0.305 to 0.610 m (1.0 to 2.0 ft.) intervals in an attempt to observe vertical variations in the induced head. Pressure transducer observations from each interval were recorded with the data acquisition equipment.

Figure 4.5 is a plot of the induced head versus depth. The induced head at the top and bottom of the water column is 0.95 and 0.05 m, respectively. The plot displays rapid head loss in the top 10 m of the water column. The initial head loss, in the interval from 5 to 12 m, is slightly non-linear (concave downward) and is attributed to friction between the turbulent injection fluid and the well casing. The Reynolds number determined for this interval is 2.27×10^4 , well above the threshold for turbulent flow, providing support for this interpretation. The most significant head loss occurred in the interval from 12 to 15 m (just below the top of the well screen) and is attributed to linear aquifer and well losses and non-linear well losses in the screen. The induced head in the lower 6 m of the screen is small, but nearly constant.

Note that the induced head observed during the first four tracer tests (Section 2.2) is considerably greater than the induced head observed during the injection tests described in Section 4.2. During the tracer tests, the induced head was measured at the top of the water column in the well,

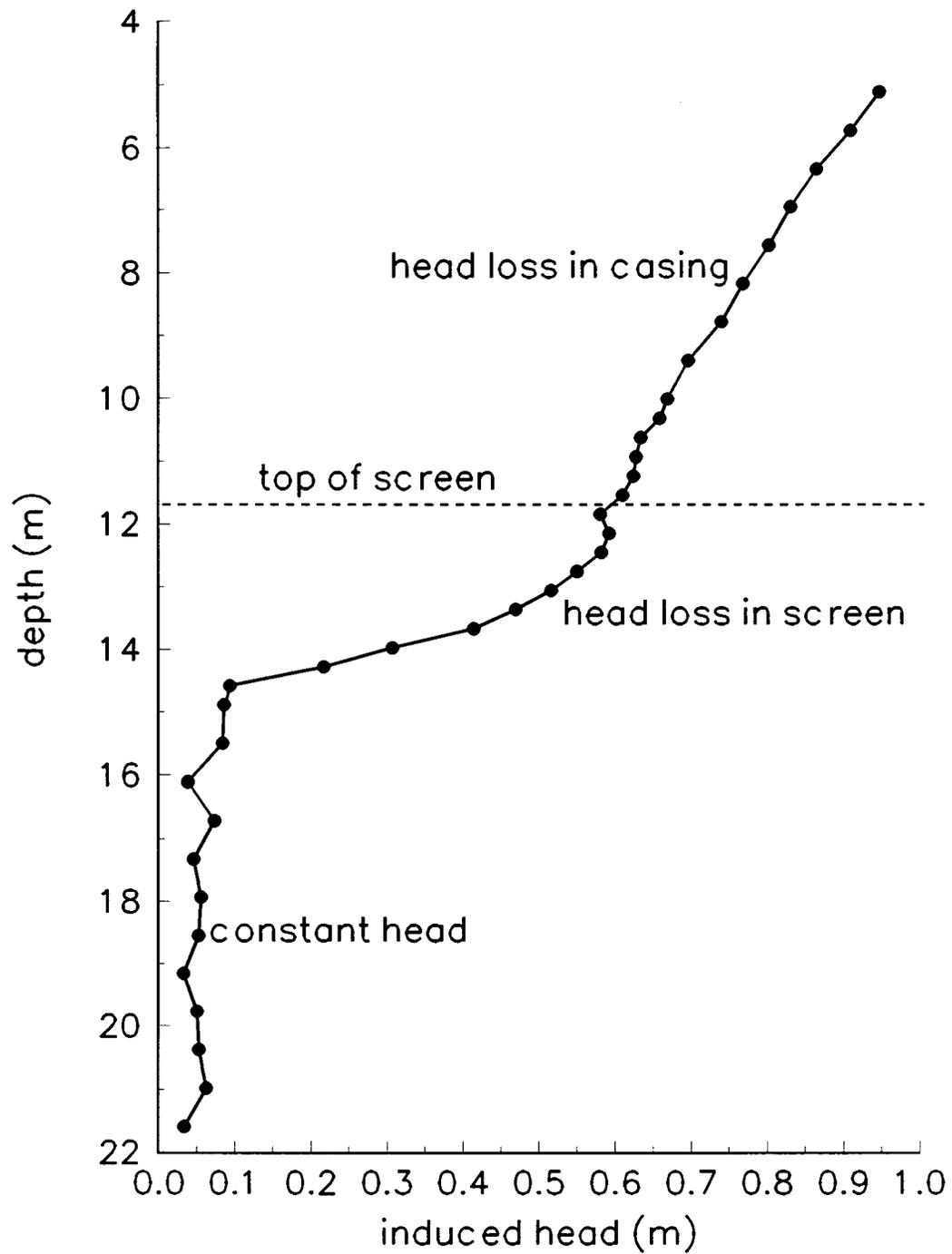


Figure 4.5 Head loss during injection in well 5-1 ($Q = 57$ L/min.).

where the induced head is greatest. During the injection tests described in Section 4.2, the induced head was measured 6.7 m below the top of the static water column, where the induced head is lower than at the top of the water column due to differential aquifer and well losses.

These observations have important implications for the tracer tests. The induced head measured during the tests is likely to be overly large due to head losses above the screen. The rapid head loss in the screen implies that most of the tracer solution entered the aquifer through the upper portion of the screened interval (12 to 15 m). Although the induction logs show that the tracer did enter the lower portion of the aquifer during the tracer tests, the tracer solution did not appear at the bottom of injection well 9-1 until 10 minutes after the initiation of tracer injection. Since the volume injected during the first 10 minutes represents several well volumes, this observation supports the hypothesis that most of the tracer entered the aquifer through the upper portion of the screen.

In an attempt to eliminate the observed vertical head variations in the injection well, a series of field experiments were performed with a perforated drop pipe that extended to the bottom of the well. The drop pipe, perforated only in the screened interval, was constructed to distribute the injection solution throughout the entire interval. Several experiments were conducted with different perforation distributions and sizes to produce a

vertical head profile that was sustainable, reproducible, and quantifiable.

The final drop pipe design is illustrated in Figure 4.6. The pipe is perforated in the lower 4.6 m of the 9.1 m screened interval. The perforations increase in size and frequency with depth.

During the final drop pipe experiments, an injection rate of 106 l/min. (28 gal./min.) was used to induce an average head of 0.09 m in injection well 5-1. Figure 4.7 is a plot of the vertical distribution of induced head after 1.5 hr. of injection. Note that the head above and below the top of the screen is relatively constant (the standard deviation of the head values is 0.005 m and is small relative to the mean, 0.089 m). This that implies the head losses observed in Figure 4.5 have been eliminated, and that a uniform distribution of injection solution exists with depth.

4.4 Tracer Solution Concentration

It is important that the change in formation electrical conductivity during tracer injection be large relative to the resolution of the borehole induction tool. If a weak saline solution is used, the increase in formation conductivity during tracer injection may be masked by noise in the readings from the induction tool. The accuracy of the induction tool used in this study, as defined by the manufacturer, is $\pm 7\%$ at 30 mS/m. Assuming an average value of 30 mS/m for formation conductivity during tracer injection,

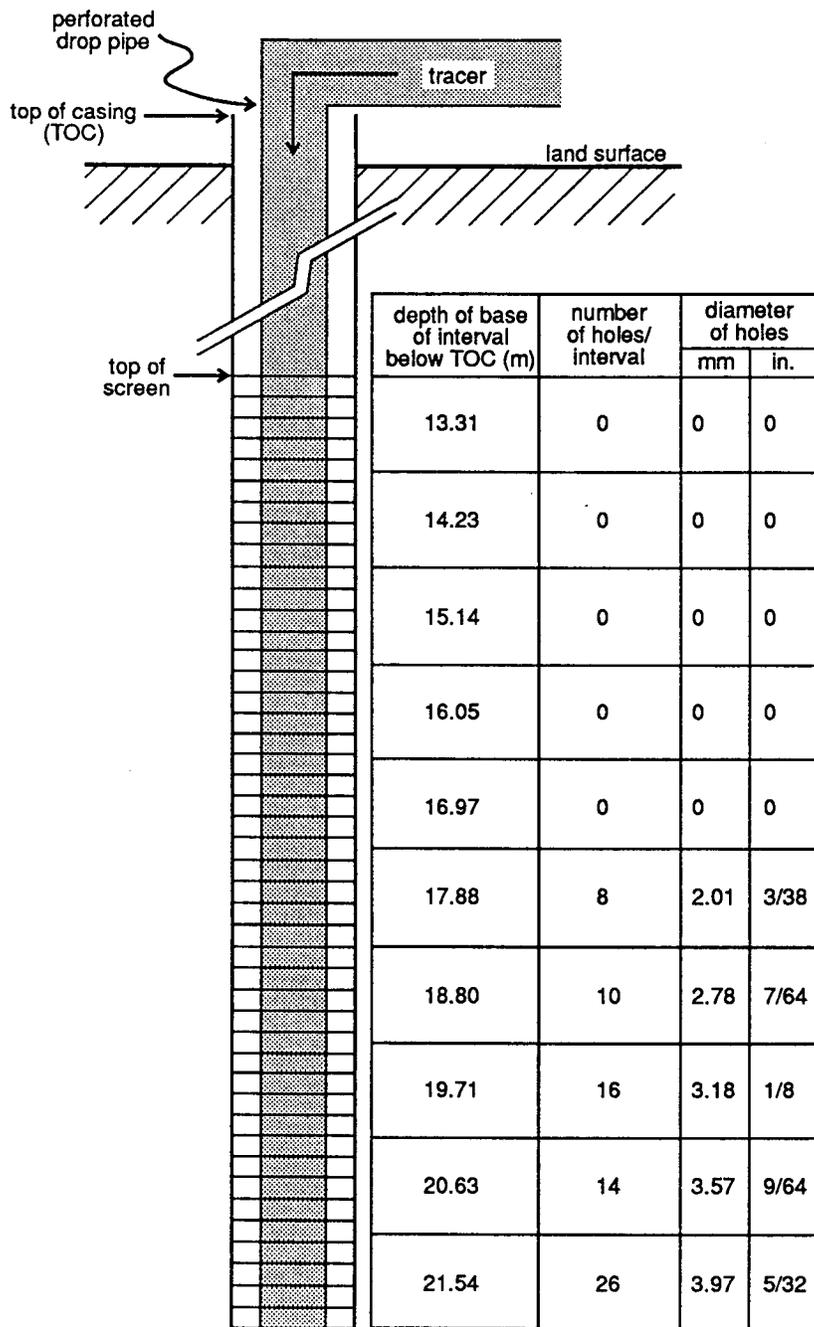


Figure 4.6 Illustration of the final drop pipe design, including the size and distribution of the perforations.

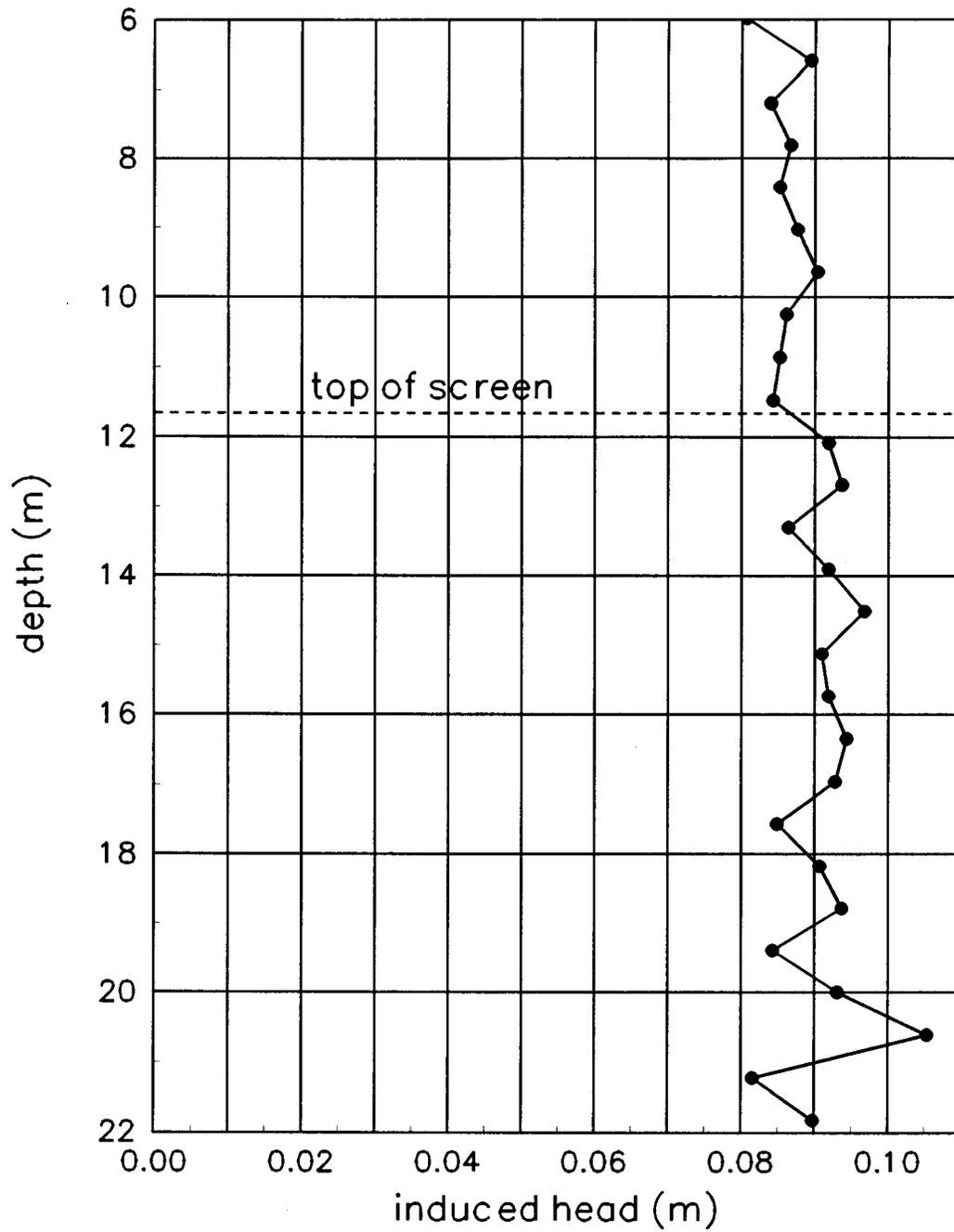


Figure 4.7 Vertical distribution of induced head in well 5-1 with final injection drop pipe design ($Q = 106$ L/min.).

this error corresponds to a range of approximately ± 1.50 mS/m.

The total maximum change in formation conductivity observed during the injection of solutions of electrical conductivity two and three times that of the background pore fluid was 6 and 14 mS/m, respectively. Clearly, the measured changes during the test conducted using a tracer solution with a conductivity twice that of background are relatively small with respect to the measured noise. To reduce the impact of this error, the electrical conductivity of the tracer solution should be at least three times that of the background pore fluid conductivity. Error in induction measurements can also be reduced if averaged values of formation conductivity from repeat logs are used rather than values obtained from a single log.

Note that increasing the salinity of the tracer in order to increase the signal to noise ratio of the conductivity measurements may induce chemical reactions within the aquifer. Significant changes in cation ratios may initiate cation exchange on clay particles. Dissolution or precipitation of minerals such as calcite and aragonite may occur due to the common ion effect or to an increase in ionic strength. Some of these reactions are kinetically fast and could alter the hydraulic properties of the aquifer during injection.

Permeameter analyses of core segments from GEMS were conducted in the Kansas Geological Survey Core Properties Laboratory to determine the extent of hydraulic property alteration due to tracer-induced chemical

reactions. The hydraulic conductivity (K) of seven cores was assessed as a function of time for a period of 130 hours. The cores were placed in a constant-head permeameter and saturated with GEMS native pore water (laboratory protocol for the permeameter analysis is described in McElwee *et al.* (1993)). After approximately 69 hours, a saline solution, similar to that used during the tracer tests, replaced the native pore water in the permeameter. Figure 4.8 contains the results of the experiment on core segment 812105. The general shape of the plot (rise and fall) is typical of most cores. The initial increase in K is attributed to core saturation. The subsequent decrease is likely due to the expansion of clay particles and the reorientation of small sediment particles. The sharp increase in K at 69 hours is due to a temporary increase in the hydraulic gradient not accounted for in the estimation of K . The gradient increase was produced by the introduction of the saline tracer solution to the constant-head upper boundary while the core was still saturated with the lower-density native water. As the tracer solution saturated the core, the gradient stabilized. The estimated K values returned to the pre-tracer level by approximately 80 hours and continued to decline at roughly the same rate as they did prior to the introduction of the tracer. These results indicate that there is no significant change in K that can be attributed to chemical reactions between the tracer solution and the aquifer material. As a result, it was concluded

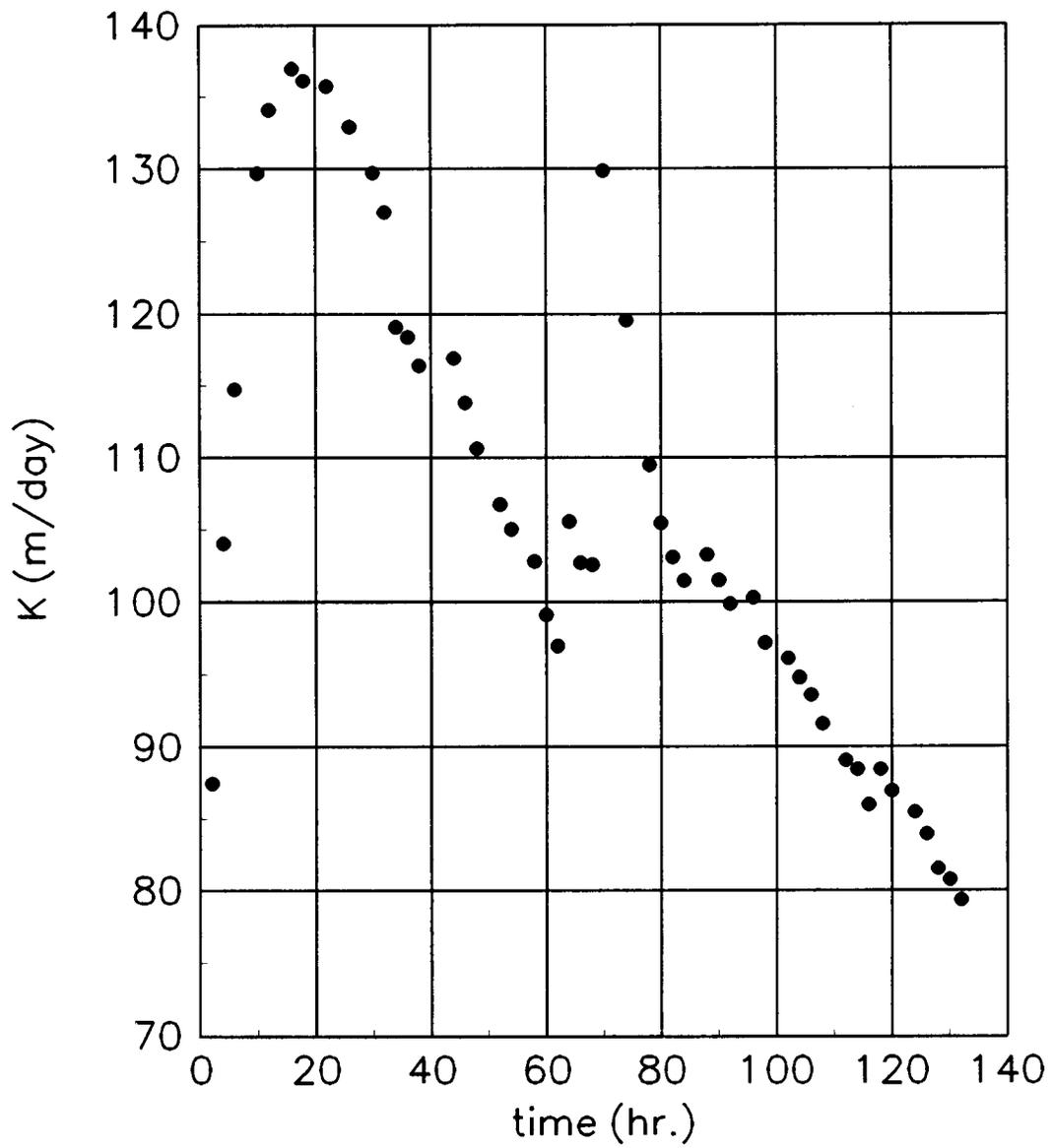


Figure 4.8 Hydraulic conductivity estimated for GEMS core segment 812105 with constant head permeameter.

that no changes in hydraulic properties occurred during the tracer tests due to the introduction of the saline solution into the aquifer.

CHAPTER 5 REPEATED TRACER TEST

5.1 Introduction

Based on the results of the investigations described in the previous chapter, a second tracer test was conducted at GEMS well 5-1 using the revised procedure. Refinements were also made to the Taylor and Molz (1990) method of data analysis in order to improve the reliability of the parameter estimates. The results obtained from this tracer test appear reasonable considering the nature of the aquifer material and are consistent with laboratory permeameter results from the same well.

5.2 Tracer Test Methodology

With the exception of the changes described below, the repeated test followed the procedure described in Chapter 2. The tracer solvent was pumped from well 0-8 using a 0.089 m diameter submersible pump (*Grundfos* model SP 2-12). The injection rate of the tracer solution, which consisted of water from the pumping well and the concentrated tracer, was 112 L/min. (29.5 gal./min.). The head in the injection well was monitored with pressure transducers positioned at the bottom of the well and above the top of the well screen. The induced head was estimated from static and steady-state injection water levels measured each time the injection pumps

were turned on and off. The average induced head at the bottom and top of the screened interval was 0.104 and 0.087 m, respectively. A linear interpolation between those two endpoints was used to estimate the induced head for each 0.03 m section of the screen. Note that vertical head surveys, similar to those illustrated in Figures 4.5 and 4.7, were taken during the test. All four surveys showed a trend of linearly increasing head with depth. Since the sample interval for the head measurements was significantly greater than the sample interval of the induction tool measurements, these data could not be easily used for parameter estimation. As a result, the average slope of the head distribution was determined and used as described above.

Due to the lack of sufficiently close observation wells, the effective radius (r_e) could not be measured. An empirical estimation of the average maximum radius of tracer invasion (2.62 m) was assumed for r_e using the procedure described in Section 5.3.3. This is a reasonable assumption because Equation 14, which is used for hydraulic conductivity estimation, is insensitive to small variations in r_e .

Prior to each induction logging period, tracer injection was terminated, and the drop pipe and pressure transducers were removed from the injection well. This procedure was necessary because there was not room in the injection well for all of the equipment at the same time.

Termination of injection is assumed to have had little influence on the movement of the tracer due to the small amount of time required to log the well (approximately 15 min.) relative to the groundwater velocities, and the small amount of time necessary to achieve steady-state flow conditions following the initiation of injection (determined from pressure transducer observations to be approximately 1.5 min.). The well was logged four times before and at the end of tracer injection and twice during six timed intervals during injection. While not in use, the induction probe was lowered in a nearby well to keep the probe in thermal equilibrium with the groundwater. The specific conductivity of the background groundwater and injection solution was 60.8 and 193 mS/m, respectively (see Appendix A.1 for determination of specific conductivity values). Tracer injection lasted for 5.70 hr. During this time, 38,240 L (10,100 gal.) of tracer solution, including approximately 37 kg of NaCl, was injected into the well. Remedial pumping removed approximately 60 % of the NaCl (see Appendix A.2 for details).

5.3 Data Analysis

5.3.1 Tracer Injection

Figure 5.1 displays average formation electrical conductivity logs obtained before, during, and after tracer injection (data in Appendix B). As the tracer invaded the aquifer, the measured formation conductivity

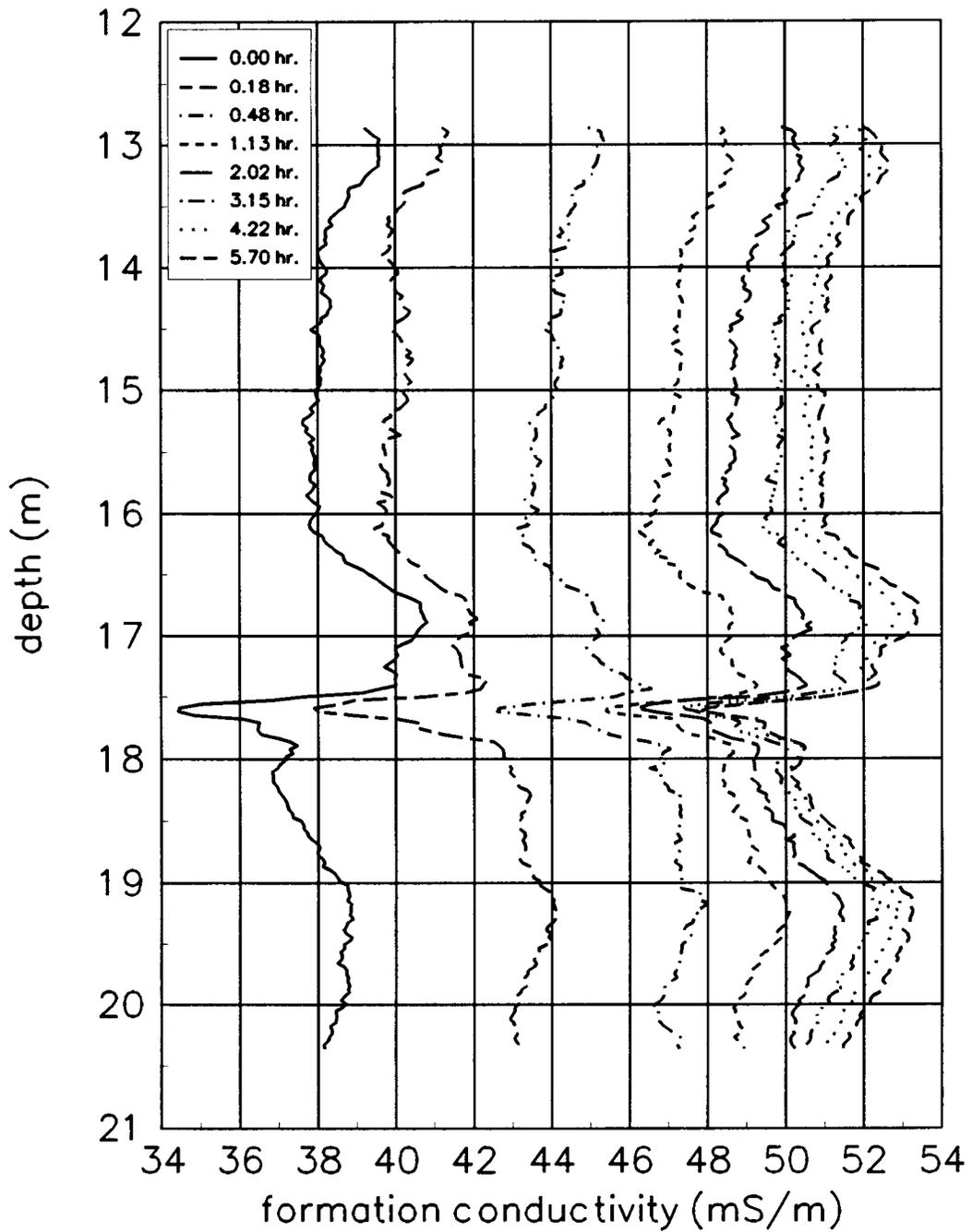


Figure 5.1 Average formation conductivity before, during, and after the second tracer test in well 5-1.

increased. Note that much of the variation existing prior to injection (log at 0.00 hr.) remains after the tracer solution approached the radial detection limit of the induction tool (log at 5.70 hr.). This implies that even when the aquifer is saturated with the saline tracer, the contribution of the matrix conductivity to the total formation conductivity dominates the combined contribution from the porosity and pore fluid. It is possible that some of the increase in formation conductivity is a result of induction tool drift. However, an analysis of induction tool drift, which is described in Appendix A.3, indicates that the effect of tool drift during the test is quite small.

The Taylor and Molz (1990) method of parameter estimation summarized in Chapter 3 assumes that tracer injection continues until the invading solution moves beyond the radial detection limit of the induction tool. After that time, the formation conductivity will not change with continued injection. Figure 5.2 displays the change in formation conductivity during tracer injection at four arbitrarily chosen intervals in well 5-1. In all four intervals, the formation conductivity appears to be asymptotically approaching an upper limit. This suggests that the tracer solution is close to the induction probe's radial detection limit at 5.70 hr. and that the assumption of tracer saturation is reasonable.

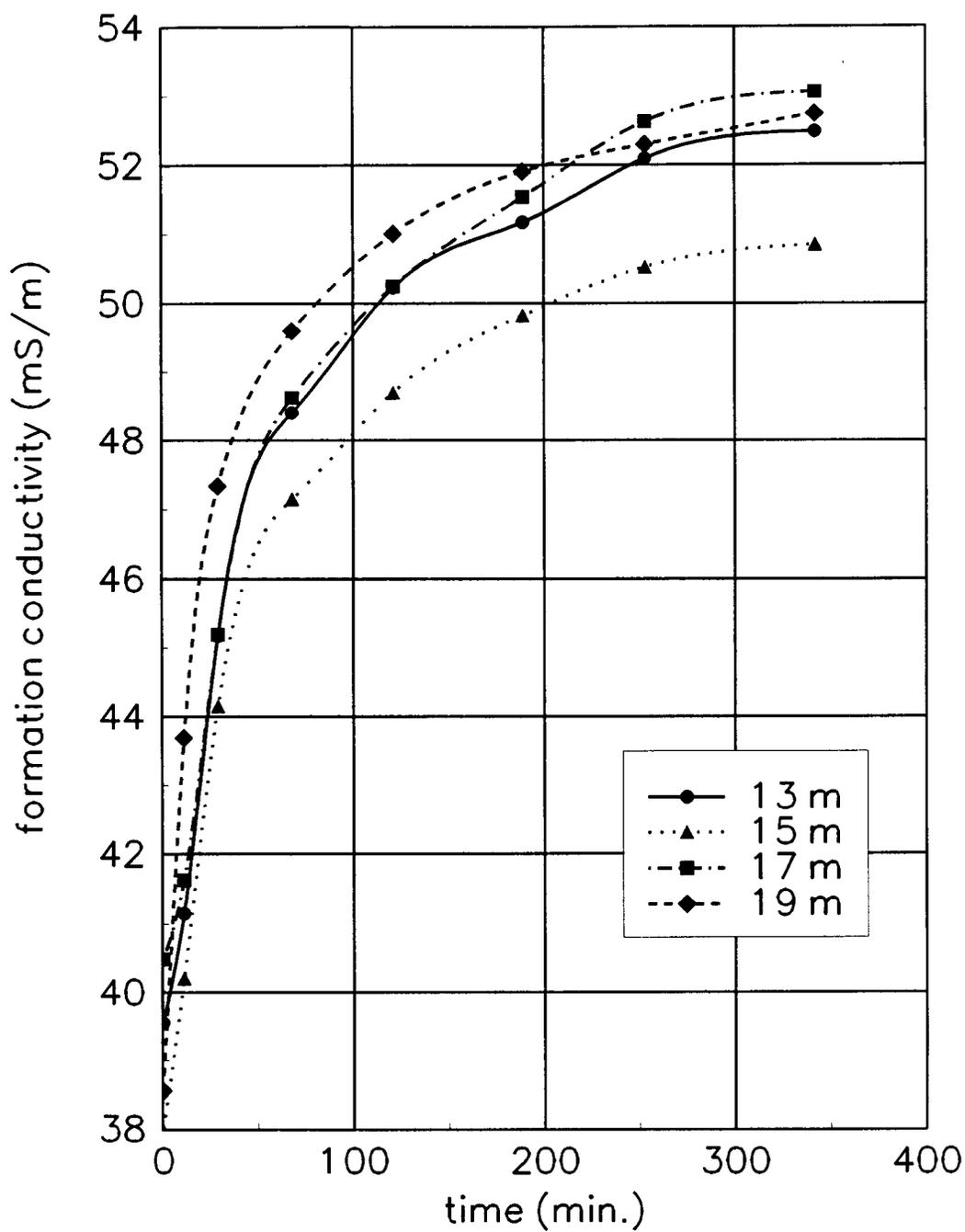


Figure 5.2 Formation conductivity during tracer injection in well 5-1 at arbitrarily chosen intervals.

5.3.2 Porosity Estimation

As stated in Chapter 3, the Taylor and Molz (1990) method of porosity estimation adopts a model of the relationship that exists between formation conductivity, pore water conductivity, and effective porosity. Equation 6 provides a means of estimating effective porosity using this model. Figure 5.3 contains calculated and measured porosity profiles for well 5-1. The solid curve is data determined by the tracer test assuming tracer solution saturation at 5.70 hr. and empirical factors $m = 1.4$ and $\alpha = 1.0$. The dotted curves are confidence intervals determined by assuming 10 % error in the empirical factors. The dashed curve is data determined from laboratory analysis of cores from the same well (Butler *et al.*, 1994). The average effective and total porosity estimates are 0.193 and 0.264, respectively. Note that the tracer test effective porosity is a minimum estimate because the tracer solution may not have entirely reached the radial detection limit of the induction tool. Figure 5.2 shows that the formation conductivity could have increased another 1 mS/m if injection had continued. However, this change would result in an increase of only 0.01 in the effective porosity estimate.

Although the tracer test values are considerably lower than the permeameter values, the tracer test values are reasonable because they represent only the interconnected pores that were filled with tracer solution

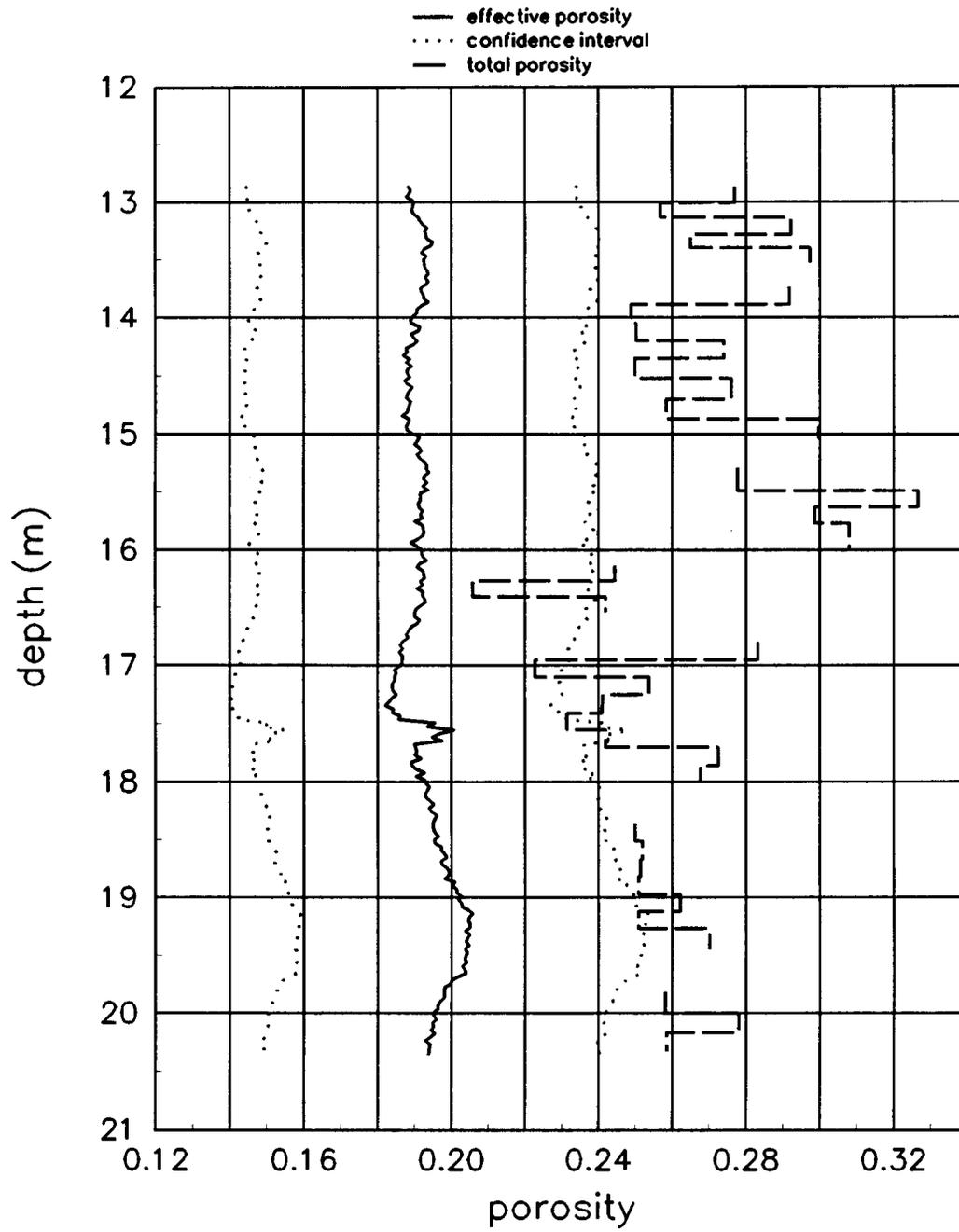


Figure 5.3 Porosity profiles for well 5-1. Total porosity from Butler *et al.* (1994).

during injection.

5.3.3 Radius of Tracer Invasion

The radial sensitivity of the induction probe (Figure 3.1) is determined theoretically from knowledge of magnetostatics and the induction probe coil geometry (Saito, 1982). The cumulative sum of these radial contributions (Figure 3.2) and Equation 7 were used to estimate the radial position of the tracer solution front for each induction log displayed on Figure 5.1.

Figure 5.4 displays the estimated radius of tracer solution invasion at several times during tracer injection using the theoretical cumulative radial response function. Empirical estimates of the average radius of tracer invasion for the entire screened interval were also made for each time that an induction log was taken during tracer injection. These estimates were made by determining the volume of aquifer invaded by the injected tracer solution assuming an average effective porosity of 0.193 and a constant tracer injection rate of 112 L/min. Figure 5.5 displays the empirical estimates along with the average theoretical radius of tracer invasion determined for each curve in Figure 5.4. These plots show that the radius of tracer invasion determined using the theoretical model is underestimated during early injection times and overestimated during later times. This observation suggests that the theoretical response function may be inappropriate in this

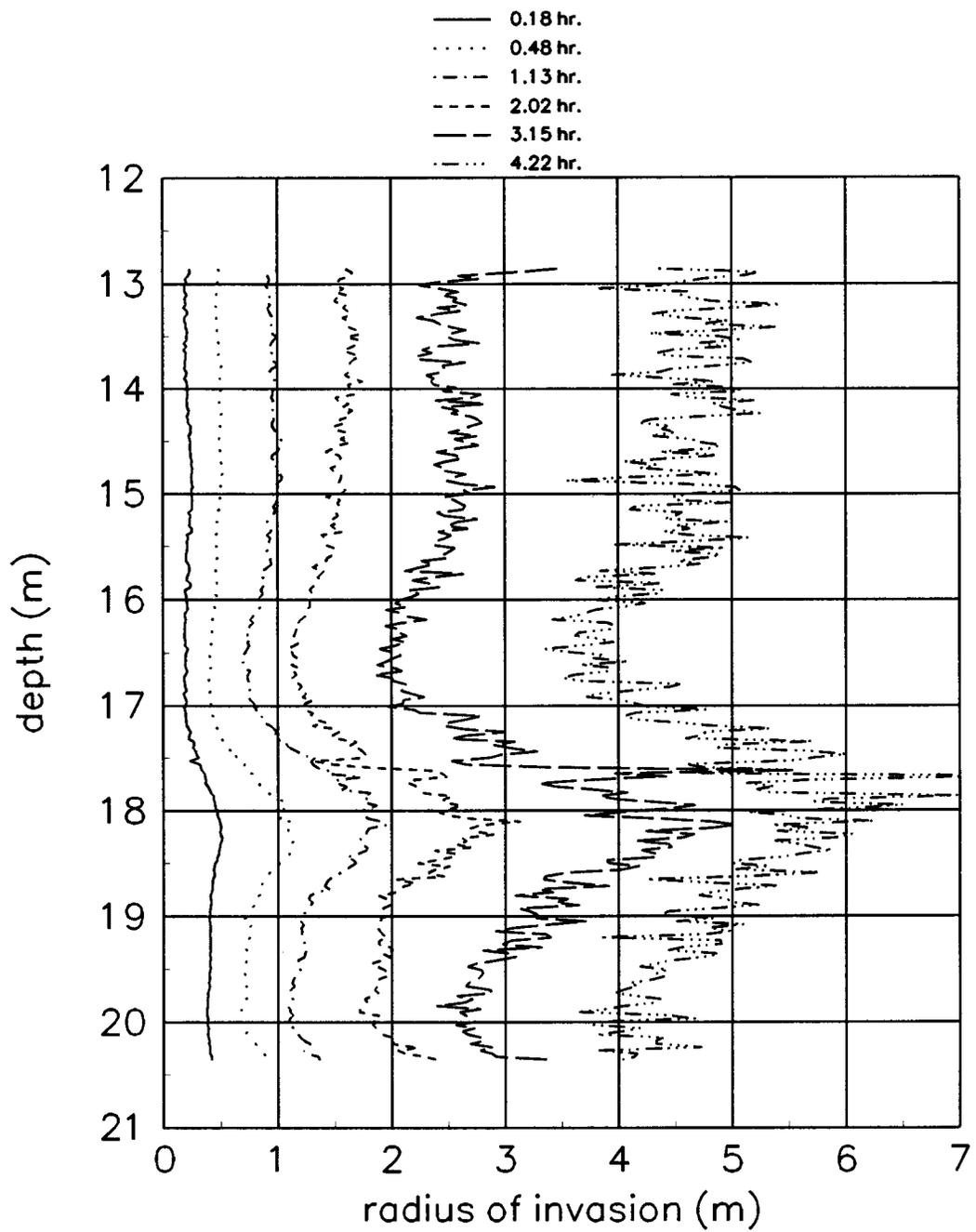


Figure 5.4 Radius of tracer invasion in well 5-1 determined with the theoretical cumulative radial response function.

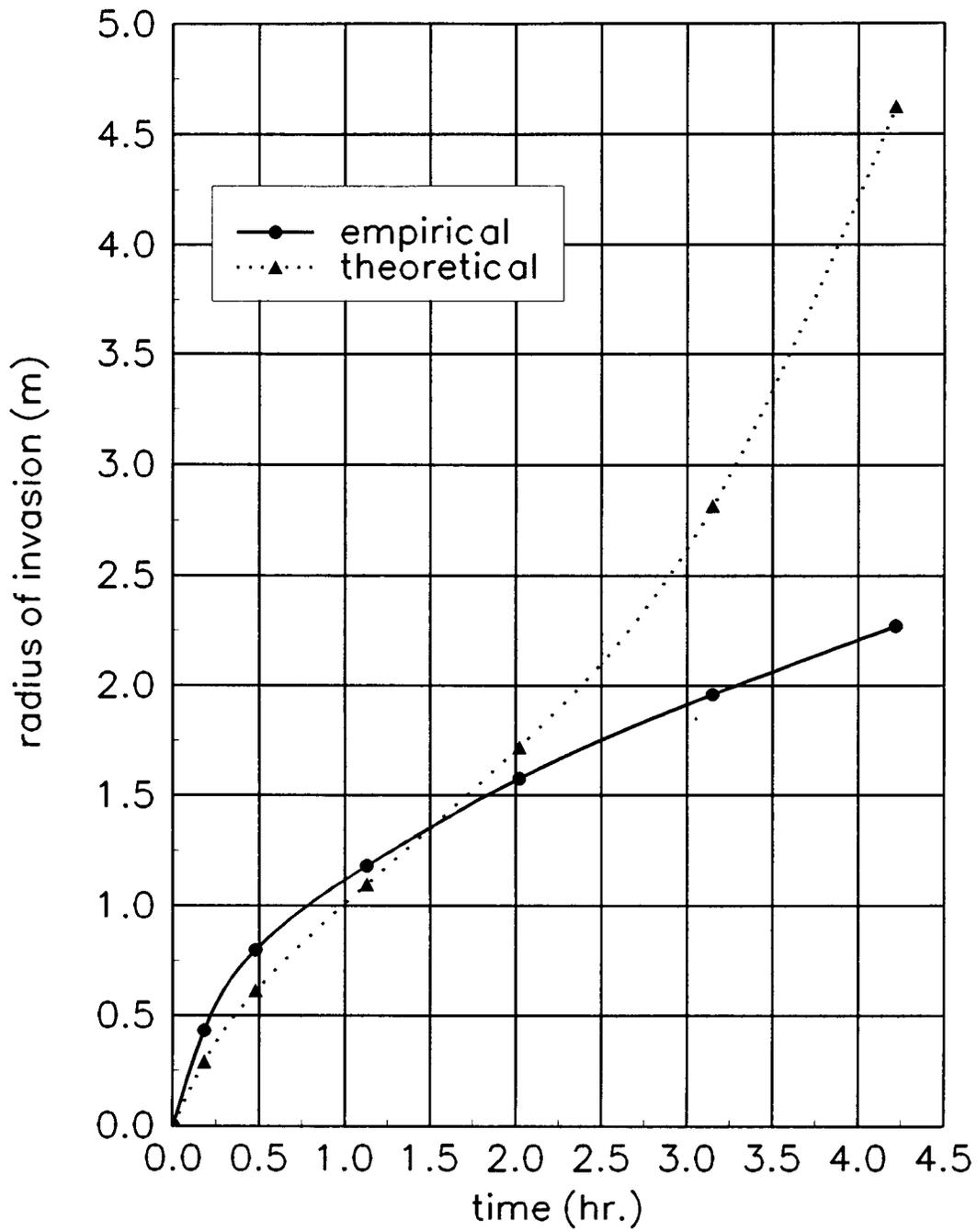


Figure 5.5 Theoretical and empirical estimates of the average radius of tracer invasion determined for the entire screened interval of well 5-1.

field environment.

Assuming the tracer reached the detection limit of the induction probe prior to the termination of tracer injection during the repeated tracer test, an empirical cumulative radial response function can be generated. The average cumulative radial response, $Z(R)$ in Equation 7, was determined for each induction log obtained during tracer injection. This value represents the percent of the total injection-induced change in formation conductivity that occurred by the time that induction log was obtained. When these values are plotted against the corresponding empirically determined average radius of tracer invasion for that time, the resulting plot is an empirically derived cumulative radial response function. Figure 5.6 displays the computed empirical cumulative radial response functions. The solid curve represents a function determined assuming the empirical estimates of tracer invasion shown in Figure 5.5. The dotted curves represent "confidence intervals" for this function. These intervals were determined from empirical estimates of tracer invasion derived from the effective porosity confidence intervals in Figure 5.3. The theoretical function is provided for comparison.

Figure 5.7 displays the radius of tracer invasion determined with the empirical response function. This figure indicates that the tracer invaded the aquifer uniformly in the interval from 13 to 16 m. Differential flow is observed

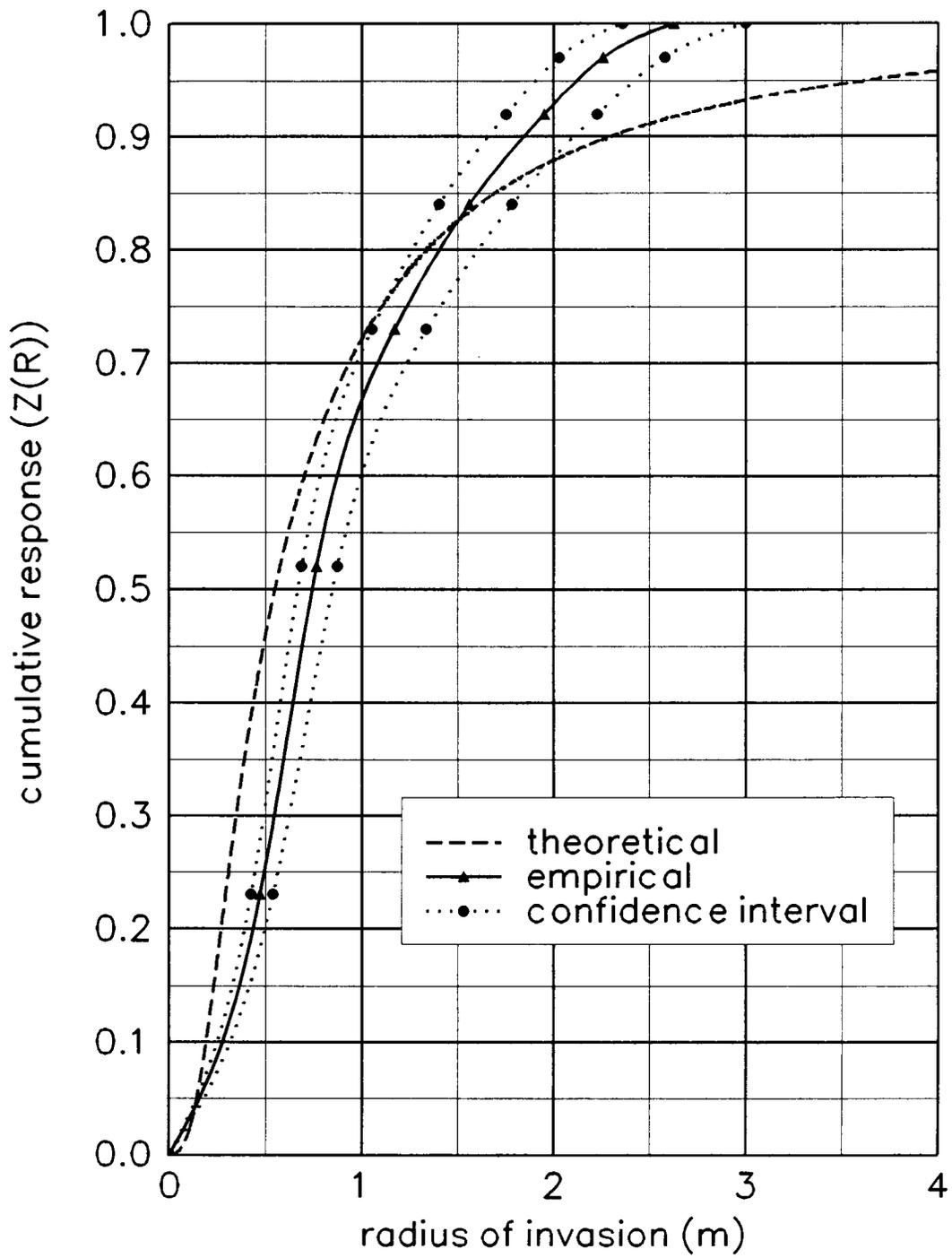


Figure 5.6 Induction tool empirical cumulative radial response functions.

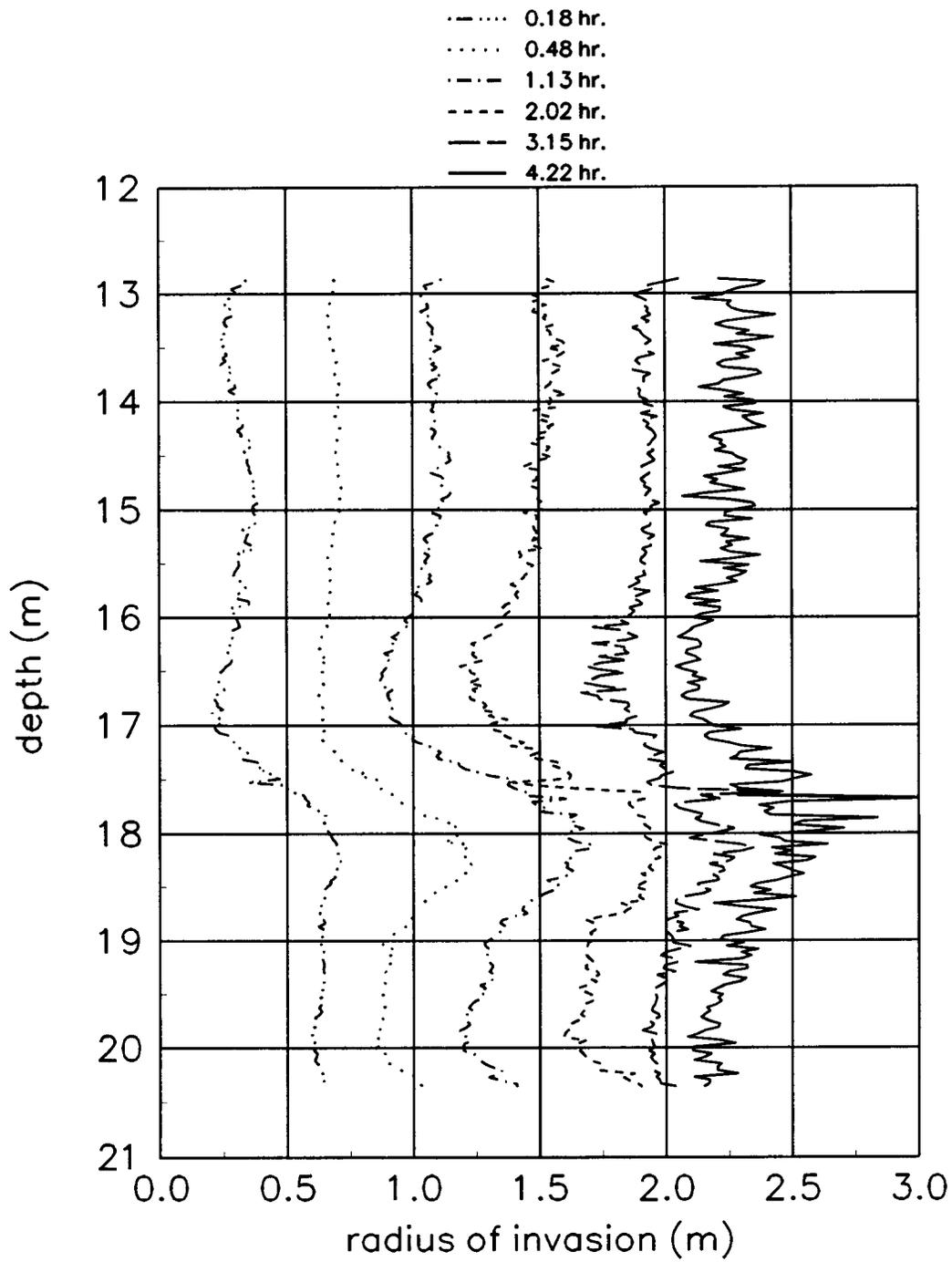


Figure 5.7 Radius of tracer invasion in well 5-1 determined with the empirical cumulative radial response function.

in the lower portion of the screened interval, with a zone of relative rapid invasion centered at 18 m.

5.3.4 Hydraulic Conductivity Estimation

Equation 14, which is used to estimate hydraulic conductivity (K), defines a linear relationship between R^2 and t (where R = radius of tracer invasion determined at 0.03 m intervals for each induction log from time t since initiation of tracer injection). Figure 5.8 is a plot of R^2 versus t determined at a depth of 17.98 m in well 5-1 using the theoretical and empirical response functions. The non-linearity observed in the theoretically determined values further demonstrates the previously discussed inappropriateness of the theoretical function.

According to the model proposed by Taylor and Molz (1990), all plots of R^2 versus t should be straight lines passing through the origin. A linear regression of R^2 (determined using the empirical response function) and t was performed to determine the slope and y-intercept for each 0.03 m interval of well 5-1. Figure 5.9 displays the y-intercept values. The intervals from the upper 5/8 of the screened section have consistently negative intercepts, while those from the lower 3/8 of the screened section have consistently positive intercepts.

The empirical radial response function (Figure 5.6) used to determine

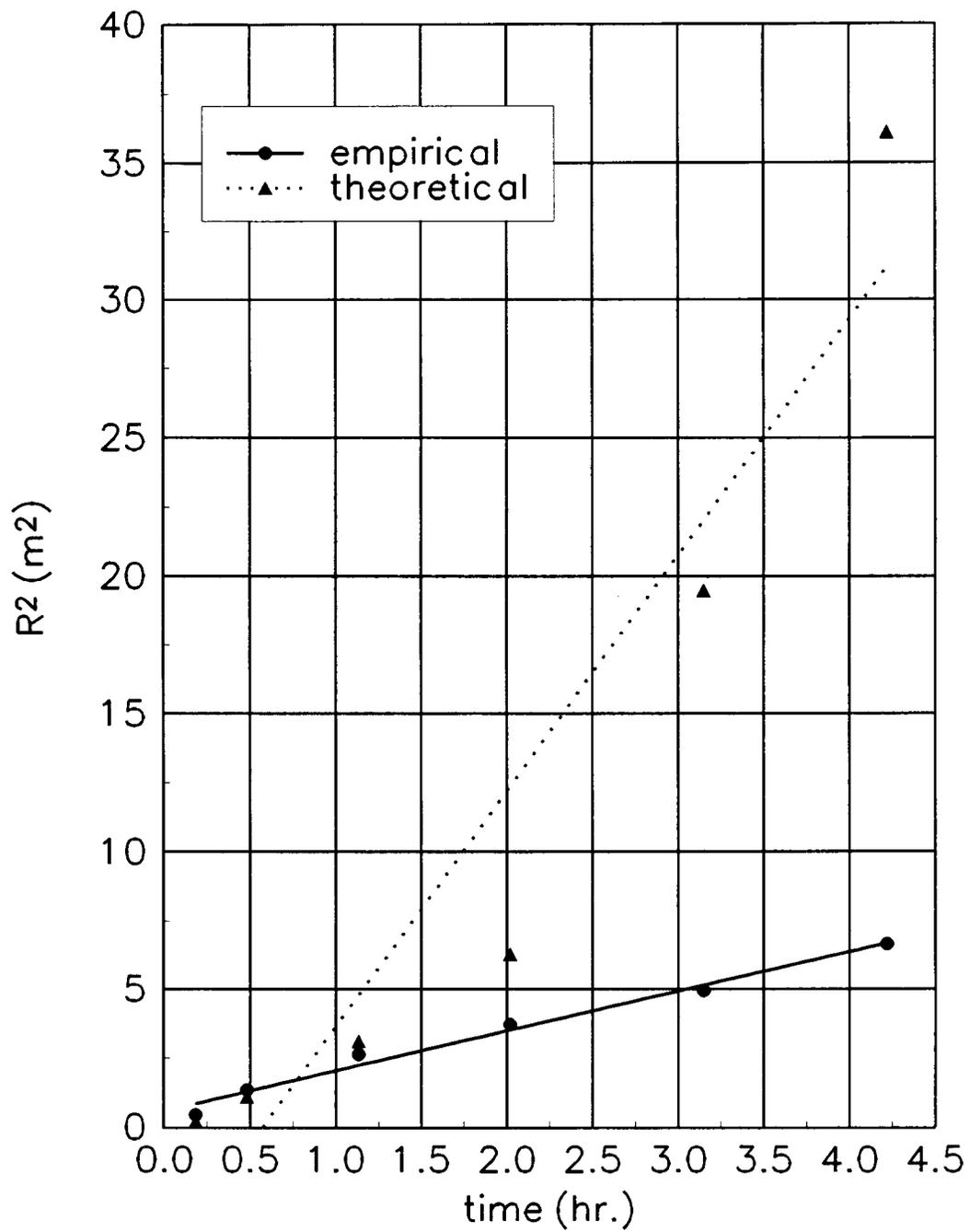


Figure 5.8 Radius of tracer invasion squared versus time determined at a depth of 17.98 m in well 5-1.

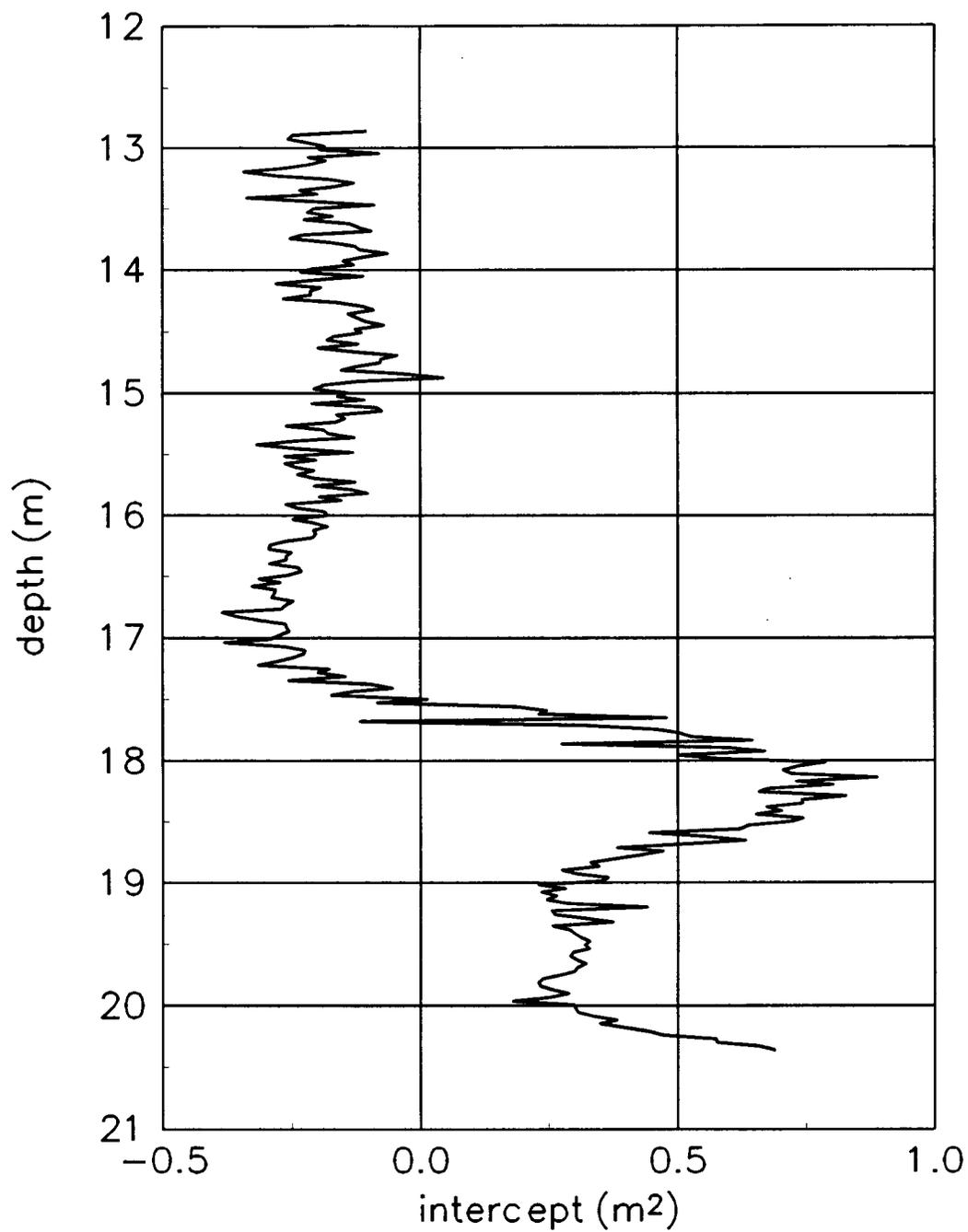


Figure 5.9 Y-intercept values from R^2 versus t plots determined for each 0.03 m interval of well 5-1.

the radius of tracer invasion is a cumulative sum of the contributions to formation conductivity from all zones within the radial detection limit of the induction tool. Therefore, the contribution to formation conductivity from a drilling-induced disturbed zone adjacent to the borehole (skin) will influence every estimate of tracer radial invasion. As a result, all estimates of tracer invasion will be shifted by a constant factor that is a function of the hydraulic properties and size of the disturbed zone. This shift is represented by the non-zero y-intercepts shown in Figure 5.9. Because the magnitude of this shift is large relative to the magnitude of the early R values, the K estimates (obtained using Equation 14) from the early R values will be severely over- or under-estimated. The K estimates obtained from later, larger R values will be less severely impacted by this skin effect. The result is a time dependence in K. Figure 5.10 displays the time dependence in K values produced by a suspected skin using the empirically derived data in Figure 5.8.

The positive and negative intercepts represent high and low permeability skins, respectively. These disturbances result from sediment churning, compaction, collapse, and smearing during drilling and development operations. The low permeability skin, represented by the negative intercepts on the upper portion of Figure 5.9, is likely due to the smearing of silt and clay from the upper alluvial unit on the inside of the

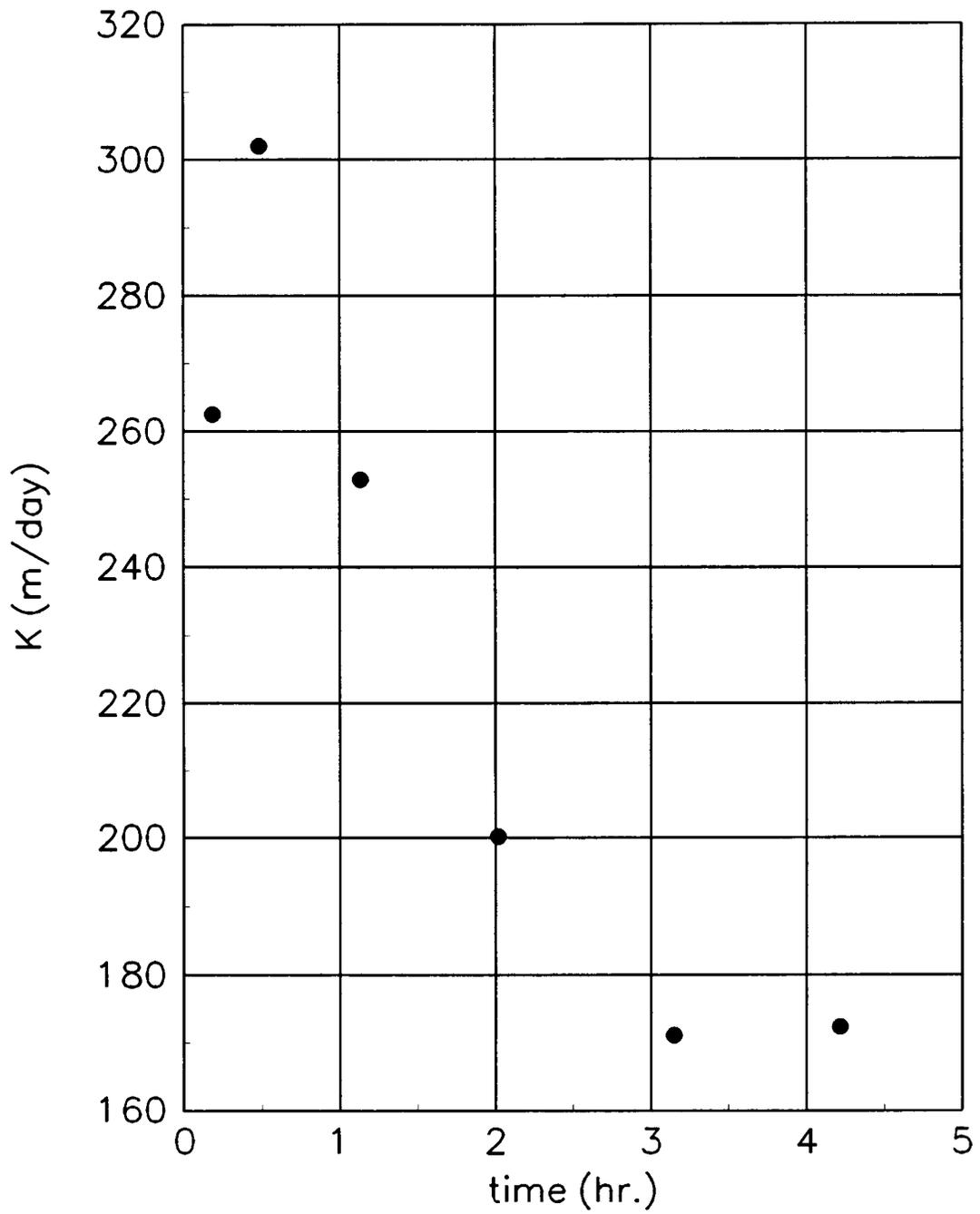


Figure 5.10 Time dependence in calculated hydraulic conductivity due to presence of a high-permeability skin at a depth of 17.98 m in well 5-1.

borehole as the auger flights penetrated the underlying sand and gravel. The abrupt change in the sign of the intercept at a depth of 17.5 m may have occurred because all of the silt and clay on the auger flights had been removed by the time the auger flights reached this depth. The high permeability skin, represented by the positive intercepts on the lower portion of Figure 5.9, likely formed due to loose grain packing as sediment collapsed on the well casing when the auger flights were removed.

These observations suggest that, contrary to the Taylor and Molz (1990) procedure, the application of Equation 14 for K estimation using values of R^2 estimated from a set of logs at a time t is not appropriate for wells with a drilling-induced disturbed zone. Values of R^2 at a certain t in Equation 14 must be replaced with the slope of the R^2 versus t plot, thereby eliminating the influence of a near-well disturbed zone introduced by the use of the individual R^2 values. Although this slope method yields only one value of K for each depth interval, it is clearly more accurate than averaging several values determined by the Taylor and Molz (1990) method.

Figure 5.11 displays hydraulic conductivity profiles for well 5-1. The solid and dotted curves are data (smoothed for visual clarity using a nine point running average) estimated with the tracer test slope method. The solid curve data are computed using $\theta = 0.193$ and R values estimated with an empirical response function derived assuming the tracer test effective

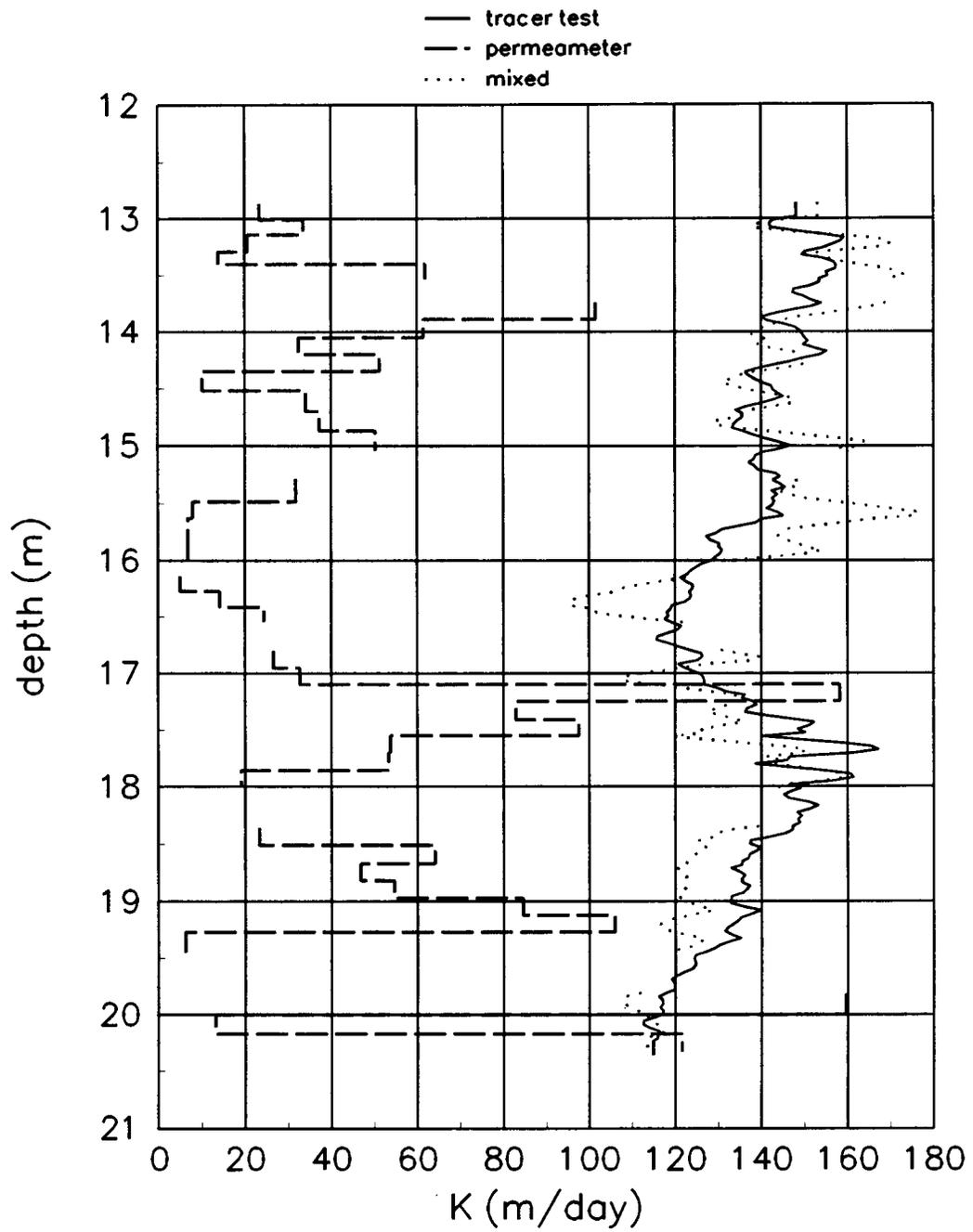


Figure 5.11 Hydraulic conductivity profiles for well 5-1. Permeameter data from Butler *et al.* (1994).

porosity (0.193). The dotted curve was computed using $\theta = 0.264$ and R values estimated with an empirical response function derived assuming the average total core porosity (0.264). The dashed curve is a plot of results from permeameter tests performed on repacked core material from the same well (Butler *et al.*, 1994).

The average tracer test and permeameter K estimates are 137 and 48.2 m/day, respectively. As expected, the tracer test values are greater than those determined from repacked sediment samples. This may be due to the original orientation of the sediment particles, which is prescribed during deposition, providing less resistance to flow than randomly oriented grains in a repacked sample. The tracer test and permeameter data show good correlation of relative spatial trends in K. Both data sets display a low permeability zone centered at approximately 16.0 - 16.5 m.

The average tracer test K estimates determined with different empirical response functions are very similar. The K estimates obtained assuming tracer-test-determined effective porosity and core total porosity are 137 and 134 m/day, respectively. K values were also calculated (but not displayed on Figure 5.11) using values of R computed from the "confidence interval" response functions in Figure 5.6. The average porosity values used to construct these response functions are 0.148 and 0.238. The corresponding K estimates are 154 and 136 m/day, respectively. These

average K estimates represent a wide range of porosity values (coefficient of variation (standard deviation / mean * 100 %) = 24.2 %), but display relatively little variation (coefficient of variation = 6.6 %). This observation suggests that the tracer test model for K estimation is not sensitive to error in the porosity estimation.

It is important to note that the tracer test parameter estimates shown in Figure 5.11 are not simple averages over the discrete intervals shown in the figure. Figure 3.1 displays the relative magnitude of radial averaging for each measured induction value. The tool also averages contributions in the vertical direction. This radial and vertical averaging masks some natural variation. Permeameter tests performed on cores and repacked sediment samples produce parameter estimates that are averages over a much smaller volume. These parameter estimates show considerably more variation, but are biased because they either represent flow normal to bedding planes or flow through disturbed samples. In short, the tracer test parameters are averages over a larger aquifer volume than the permeameter parameters, but are more accurate estimates of the horizontal component of hydraulic conductivity because they represent *in situ* observations made under conditions of lateral flow.

A final check on the absolute magnitude of the tracer test K estimates can be performed by comparing the average of the estimates to an average

K determined for the whole screened interval from the Thiem Equation (Kruseman and de Ridder, 1990):

$$K = \frac{Q}{2\pi bH} \ln\left(\frac{r_e}{r_w}\right) \quad (15)$$

If Q (discharge) = 161 m³/day, b (aquifer thickness) = 9.14 m, H (average induced head) = 0.096 m, r_e (effective radius) = 2.62 m (assumed to equal the average maximum extent of tracer invasion), and r_w (radius of well) = 0.025 m, then K = 136 m/day. This value compares very well to the figure of 137 m/day estimated by averaging the K values determined for each vertical log interval. The similarity in these estimates suggests that the magnitude of the tracer test K estimates is accurate.

5.4 Comparison of the Two Tests in Well 5-1

As a result of the refinements to the Taylor and Molz (1990) method discussed in Chapter 4, the K estimates of the two tracer tests in Well 5-1 are significantly different. The primary reason for the differences in the estimates from these two tests is the use of the drop pipe, which minimized the introduction of air into the aquifer and produced a near constant head distribution in the injection well.

A comparison of the formation conductivity logs obtained before, during, and after the two tracer tests (Figures 4.1 and 5.1) clearly reveals the

success of the drop pipe. A rapid increase in formation conductivity is shown in the upper portion of the screened interval in Figure 4.1. This rapid increase is likely the result of an overly large rate of tracer invasion into this interval produced by the nonuniform head distribution shown in Figure 4.5. As a result of the use of the perforated drop pipe during the second test, a near uniform head distribution was obtained. The formation conductivity logs for this test (Figure 5.1) do not display the rapid increase in formation conductivity in the upper portion of the screened interval.

The drop pipe also minimized the introduction of air into the aquifer during the second test. The electrical conductivities of the tracer solutions for the two tests were essentially the same. As a result, if complete tracer saturation occurred during both tests, the total change in formation conductivity measured during tracer injection should be the same for both tests. However, due to the introduction of air into the aquifer during the first test, the average change in formation conductivity (7.2 mS/m) was significantly lower than the average change observed during the second test (13.2 mS/m). Another difference between the tests which may be attributed to the introduction of air into the aquifer is the lack of tracer invasion in the central portion of the screened interval during the first test. This zone is identified by the very small change in formation conductivity seen between 15.5 and 16.5 m on Figure 4.1. Figure 5.1 shows no evidence of this feature

in the second test. It is hypothesized that the pore spaces in this interval became preferentially clogged with air bubbles during the first test, thereby reducing the porosity and hydraulic conductivity of the interval.

The parameter estimates from the two tests are also significantly different. The average effective porosity estimated from the logs of the first and second tests is 0.121 and 0.193, respectively. The average hydraulic conductivity estimated from the first and second tests is 2.04 and 137 m/day, respectively. The parameter estimates from the second test agree most closely with the results of previous studies at the same well (Butler *et al.*, 1994). This better agreement is attributed to the improved procedures employed in the second test.

5.5 Geologic Interpretation

The results of the final tracer test and data from core retrieved during the installation of the injection well provide insight to the near-surface geology at GEMS. Figure 5.12 displays a generalized stratigraphic section and plots of subsurface properties for well 5-1. The formation conductivity and natural gamma logs obtained during a pre-tracer test survey reveal a fining-upward sequence composed of two distinct units of roughly equal thickness (approximately 11 m).

X-rays of core display cross-bedded sand and gravel and clay

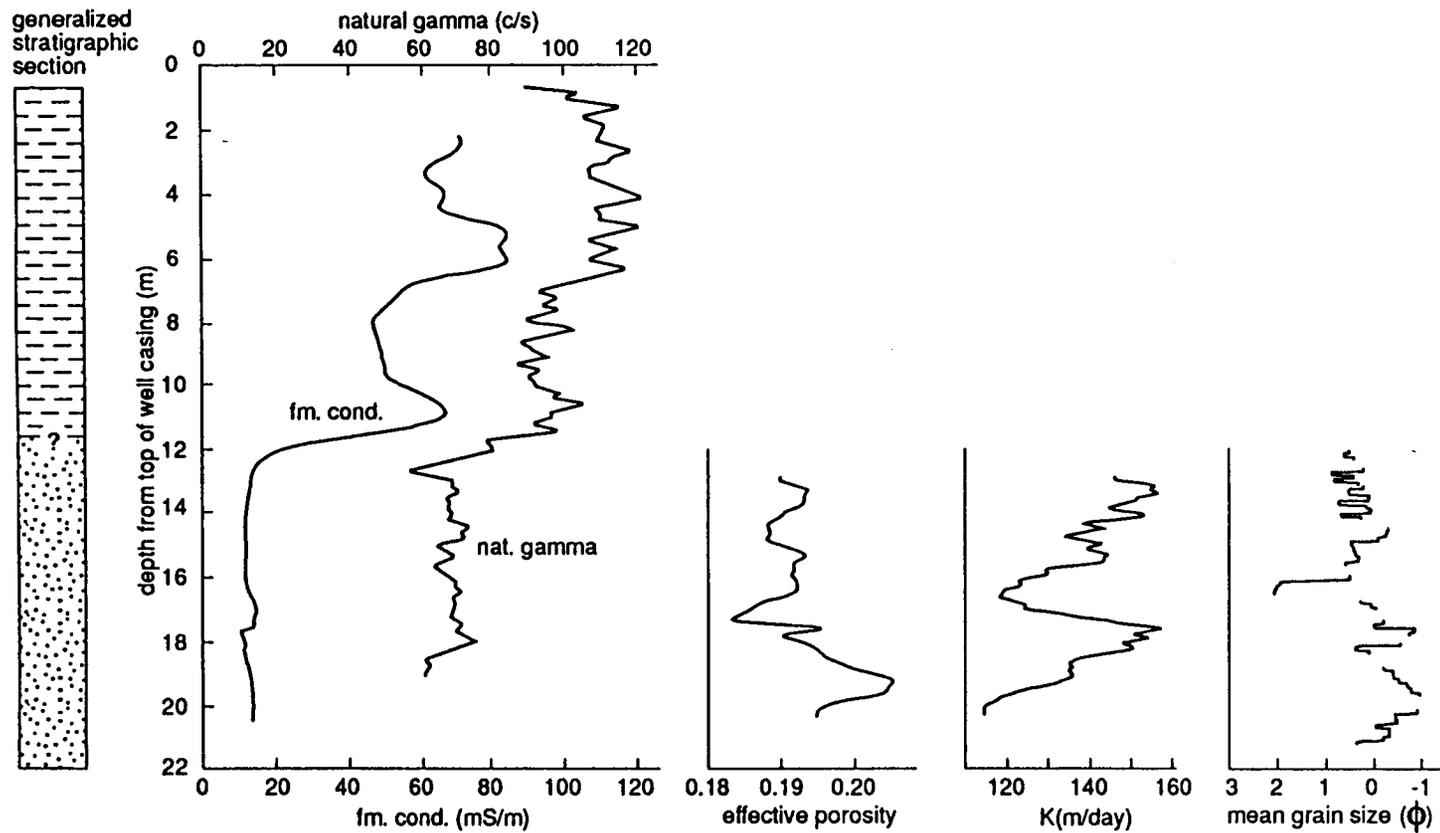


Figure 5.12 Generalized stratigraphic section and correlative plots of subsurface properties for well 5-1. Dashed and dotted portions of stratigraphic section refer to silt and clay, and sand and gravel, respectively. Mean grain size data from McElwee et al. (1993).

drapes in the lower unit, indicating fluvial deposition (Blatt *et al.*, 1980). Sieve analyses of unconsolidated core sediment from this unit (McElwee *et al.*, 1993) display a fining-upward trend (Figure 5.12), typical of fluvial channel deposits (Allen, 1965). The fining-upward trend is not observed as a decreasing-trend in tracer test K (Figure 5.12). This may be the result of variations in particle sorting and packing during deposition. The mean K displayed on Figure 5.12 is 137 m/day, typical of silty to clean sands (Freeze and Cherry, 1979). The mean tracer test effective porosity displayed on Figure 5.12 is 0.193. This value is low for unconsolidated sands (typically 0.25 - 0.50, Freeze and Cherry, 1979) and may be attributed to poor particle sorting and tight particle packing. Figure 5.12 displays no consistent correlation between effective porosity, K, and grain size.

Cores from the upper unit are composed of silt and clay. This interval appears homogenized by bioturbation, and contains rootlets and organic matter. These features indicate subaerial exposure.

The basal sand and gravel alluvial unit is interpreted as laterally accreted river channel deposits. The overlying silt and clay alluvial unit is interpreted as vertically accreted floodplain deposits. It is likely that the two units represent a single lateral migration of the Kansas River.

Chapter 6 Conclusion

The borehole induction single-well tracer test appears to be theoretically sound. It has considerable potential for accurate and detailed characterization of vertical variations in effective porosity and the radial component of hydraulic conductivity. Modifications of the originally proposed procedure have been made to ensure that the model assumptions are valid, to reduce monitoring error, and to accommodate common drilling-induced disturbances. A perforated drop pipe was used to eliminate the introduction of air into the aquifer during tracer injection and to create a near-uniform head distribution in the injection well. Averaged repeat induction logs were used for parameter estimation in order to increase accuracy by decreasing noise in the induction probe readings. The theoretically determined cumulative radial response function was replaced with an empirically derived function that preserved mathematical relationships defined by the theoretical analysis model. Finally, modifications were made in the method of data analysis such that the technique can be used for wells with both high and low permeability skins.

APPENDIX A

A.1 Estimation of Tracer Solution Electrical Conductivity

As stated in Section 2.5, a fluid conductivity cell in the injection line monitored the electrical conductivity of the tracer solution. During tracer injection, the fluid in the injection line was under considerable pressure (approximately 3.4×10^5 N/m² (50 psi)). This pressure appeared to affect the accuracy of the conductivity cell. As a result, no reliable measurements of the tracer solution conductivity were obtained in the field.

The tracer solution conductivity used for parameter estimation was estimated from the conductivity of the discharge during the first hour of remedial pumping. This procedure assumes the discharge was not diluted with fresh groundwater during remediation.

In order to correct error in the remedial discharge conductivity measurements due to a change in calibration of the conductivity cell during the high-pressure injection, the cell was recalibrated in the laboratory and the measurements were adjusted appropriately. Figure A.1 contains the calibration curves. The dashed line is data from the CRC Handbook of Chemistry and Physics (1989), while the solid line is data calculated in the laboratory using precise measurements of salt mass and water volume. The slopes of these lines (158.2 and 175.7) were used to determine a correction

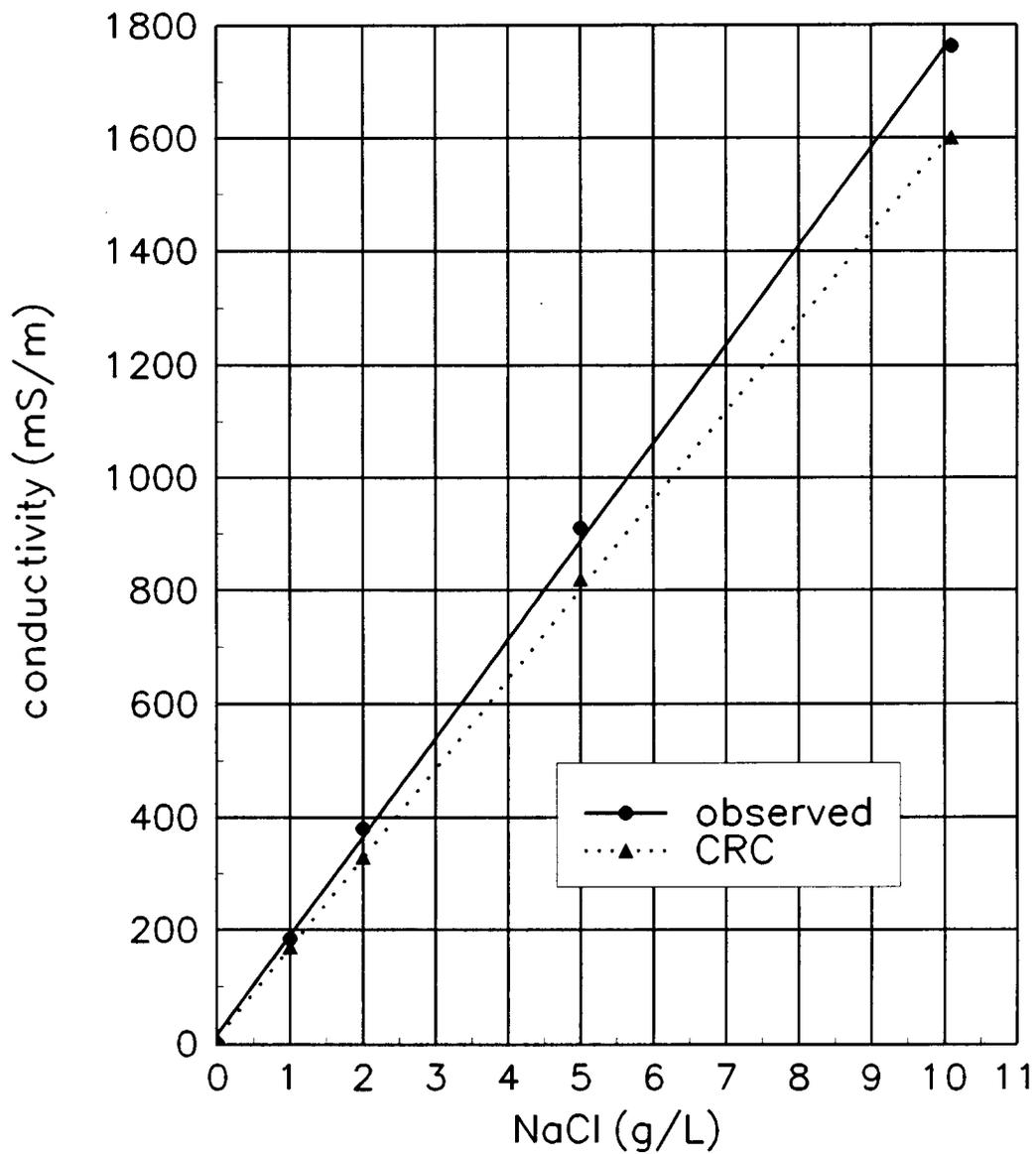


Figure A.1 Calibration of fluid conductivity cell. Data denoted by triangles from CRC Handbook of Chemistry and Physics (1989).

factor, 0.900, for the field values. The average specific conductivity measured during the first hour of remedial pumping was 214.0 mS/m. The corrected value used for parameter estimation was 192.6 mS/m. The background conductivity value measured from discharge from nearby well 1-7 was 67.6 mS/m. The corrected value was 60.8 mS/m.

Note that it was attempted to determine the specific conductivity of the injection fluid using the mass of salt and the volume of water injected during the test. This procedure was abandoned because an accurate measurement of the mass of salt was not obtained.

A.2 Remediation of Well 5-1

Remedial pumping began immediately after the completion of the post-injection geophysical logging. The procedure used is the same as that described in Section 2.6. The pump head was lowered to the bottom of the well, allowing water to be withdrawn from the entire thickness of the aquifer. The average discharge rate was 118 L/min. (31.2 gal./min.) and the duration of pumping was 10.07 hr. During this time, the discharge fluid conductivity declined from 193 mS/m to 62 mS/m. The pump head was then raised to approximately the center of the screened interval of the well (4.9 m from the bottom of the well), enabling water to be withdrawn primarily from the upper portion of the aquifer. The average discharge rate was 98.4 L/min. (26.0

gal./min.) and the duration of pumping was 5.7 hr. During this time, the discharge fluid conductivity declined from 66 mS/m to 62 mS/m. At this time, the pump head was lowered to the bottom of the well where discharge continued at 114 L/min. (30.1 gal./min.) for 2.8 hr. The discharge fluid conductivity was at or below the background level during this entire withdrawal period (60 - 61 mS/m). A total of 124,400 L (32,870 gal.) of water was removed during remediation. This volume is equivalent to 3.25 pore volumes. An approximate mass balance indicated that 60 % of the tracer mass had been removed

Following remedial pumping, the formation conductivity of the injection well was logged in order to assess the results of the remediation. Figure A.2 is a plot of formation conductivity before and after tracer injection and after remedial pumping. Each plot is an average of 4 logs. These logs indicate that significant tracer remained in the aquifer in the interval from 15 to 17 m. It is possible that the tracer remained in this interval following remedial pumping because other units were more readily flushed.

A contaminant transport model was used to determine if the remaining tracer in the aquifer following remedial pumping posed a threat to other water users in the area. The nearest production well in the alluvial aquifer is located approximately 12 m from the injection well. A converging radial flow model (Welty and Gelhar, 1994) was used to estimate the tracer

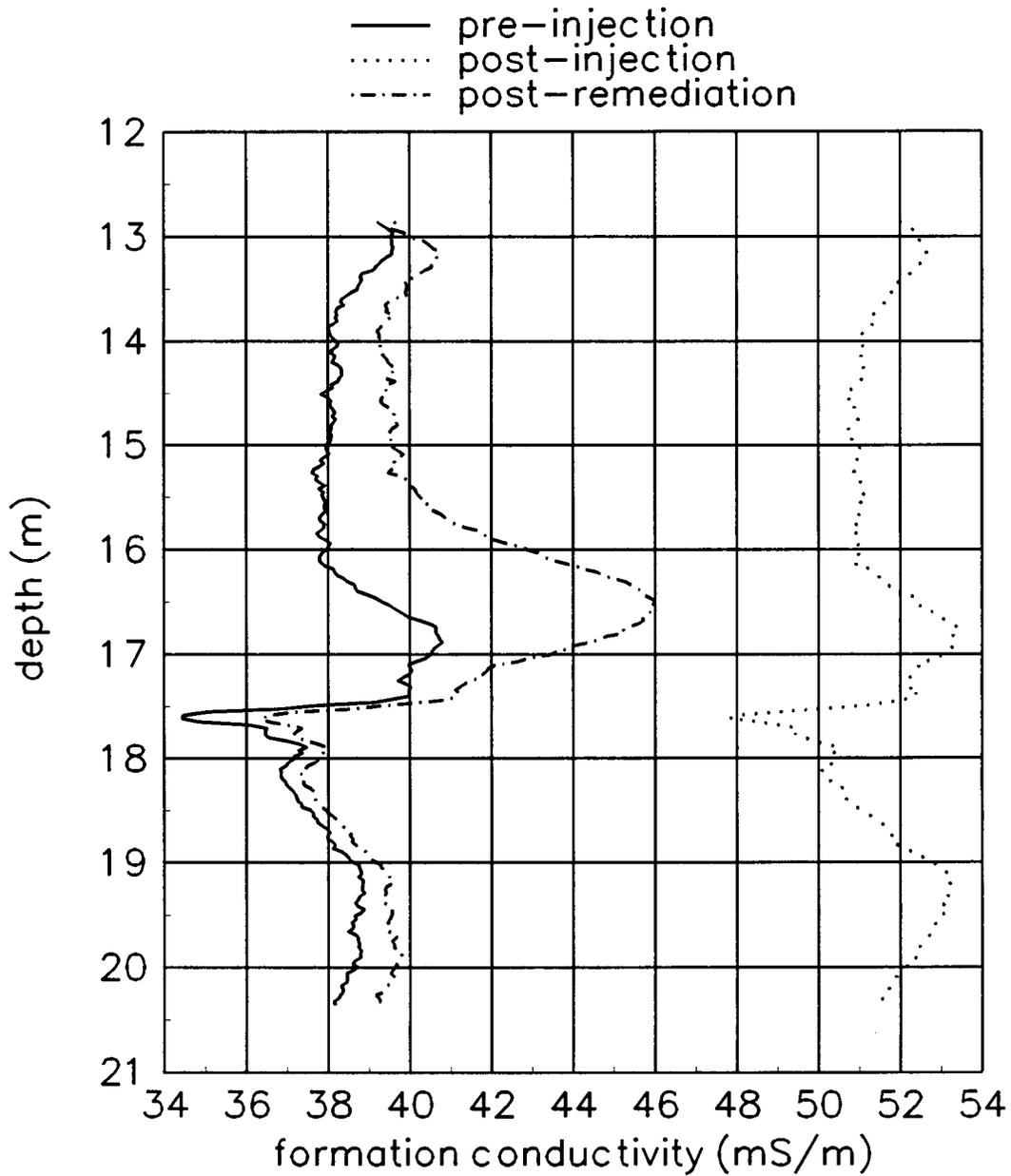


Figure A.2 Average formation conductivity before and after tracer injection and after remedial pumping in well 5-1. Pump head positioned at approximately 21.5 and 16.6 m during remedial pumping.

breakthrough concentration at the production well during normal use (approximately 379 L/min. or 100 gal./min.). Assuming that the remaining tracer is a pulse at the injection well and that the longitudinal dispersivity is 1 m (estimated from Gelhar *et al.*, 1992), the estimated maximum tracer concentration is 2.6 % of the injected tracer concentration of 0.70 g NaCl/L and corresponds to 4.4 % of the E.P.A. drinking water standard of 0.250 g Cl/L (Code of Regulations, 1992). The concentration of the tracer appearing at more distant locations would be less. As a result of this simulation, it was concluded that the tracer remaining in the aquifer following remedial pumping poses no threat to other local water users.

A.3 Induction Tool Drift

Figure A.3 shows the average formation electrical conductivity logs obtained before tracer injection for the two tests in well 5-1. Note the significant difference in the magnitude of the measured conductivity values (dotted curve). This shift could be the result of several factors: thermal disequilibrium between the induction tool and the groundwater during logging, changes in groundwater temperature or chemistry with time, or changes in the instrument electronics with time. Because the induction tool was allowed to thermally equilibrate with the borehole fluid for at least 30 min. prior to each logging interval (following the manufacturer's

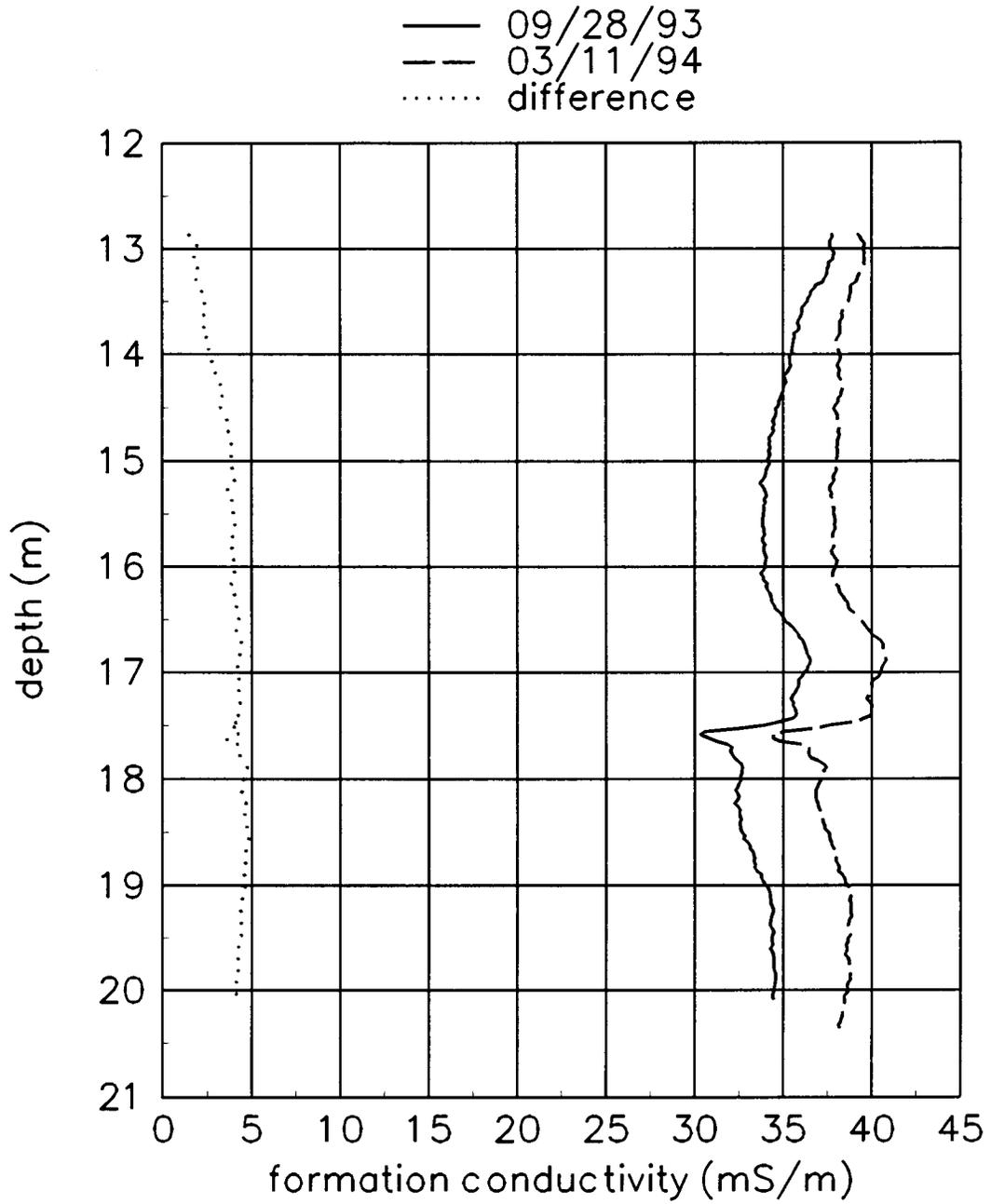


Figure A.3 Average formation conductivity logs for well 5-1 (difference = 3/11/94 value - 9/28/93 value).

recommendation), thermal disequilibrium likely did not produce the observed shift.

Young *et al.* (1993) compared conductivity logs, obtained at the same well with the same induction tool, taken weeks and months apart. Their observations identified a systematic linear increase in conductivity values with time, independent of depth and magnitude. As a result of their investigations, they concluded that the drift was likely the result of changes in the tool electronics. Since the difference in the magnitude of the pre-injection logs (Figure A.3) is relatively constant with depth and magnitude, it is likely that it is also the result of changes in tool electronics. The non-constant difference observed in the top 2.5 m of the pre-injection logs may be due to seasonal variations in groundwater temperature and chemistry.

The average rate of drift computed from Figure A.3 is 2.9×10^{-2} mS/m per day. This rate is negligible relative to the length of the injection tests and is assumed to have no influence on the results.

APPENDIX B Average Formation Conductivity Logs From Well 5-1

The following data are average formation conductivity logs obtained before, during, and after the second tracer injection in well 5-1. The pre- and post-injection logs (0.00 and 5.70 hr.) are averages calculated from four repeat logs. All other logs are averages calculated from two repeat logs. The logs are recorded in units of mS/m. The depth measurements are given relative to the top of the well casing. The time, listed above each log, refers to the duration of injection that had occurred when the log was obtained.

dep. m	0.00hr	0.18hr	0.48hr	1.13hr	2.02hr	3.15hr	4.22hr	5.70hr
12.862	39.206	41.200	44.966	48.381	49.914	51.298	51.575	51.981
12.892	39.326	41.366	45.280	48.437	50.191	51.335	51.981	52.175
12.923	39.455	41.311	45.298	48.307	50.283	51.206	52.055	52.277
12.953	39.594	41.218	45.335	48.455	50.190	51.372	52.036	52.341
12.984	39.557	41.311	45.353	48.492	50.246	51.261	52.092	52.452
13.014	39.547	41.144	45.169	48.400	50.227	51.169	52.092	52.480
13.045	39.575	41.163	45.188	48.492	50.357	51.298	51.907	52.480
13.075	39.566	41.163	45.243	48.474	50.209	51.372	52.110	52.452
13.106	39.594	41.052	45.206	48.603	50.431	51.354	52.166	52.526
13.136	39.566	41.200	45.169	48.658	50.357	51.520	52.277	52.618
13.167	39.575	41.237	45.132	48.548	50.375	51.538	52.369	52.664
13.197	39.437	41.144	45.021	48.640	50.468	51.538	52.443	52.600
13.228	39.326	40.868	45.113	48.492	50.412	51.372	52.351	52.600
13.258	39.243	40.738	44.947	48.437	50.357	51.372	52.092	52.471
13.289	39.169	40.701	44.818	48.437	50.357	51.187	51.981	52.416
13.319	39.104	40.720	44.855	48.455	50.172	51.003	52.000	52.369
13.350	38.828	40.461	44.671	48.271	50.116	50.984	51.981	52.249
13.380	38.791	40.240	44.504	48.215	50.062	50.947	51.852	52.175
13.411	38.818	40.203	44.541	48.012	49.932	50.874	51.852	52.018
13.441	38.781	40.277	44.578	48.049	49.969	50.855	51.649	51.917

13.472 38.726 40.240 44.615 48.068 50.061 50.818 51.538 51.981
13.502 38.708 40.147 44.615 48.160 49.766 50.726 51.612 51.889
13.532 38.569 40.036 44.523 47.920 49.858 50.652 51.538 51.778
13.563 38.458 40.037 44.480 47.735 49.710 50.670 51.354 51.677
13.593 38.348 39.815 44.412 47.624 49.563 50.357 51.354 51.621
13.624 38.301 39.852 44.523 47.754 49.415 50.283 51.224 51.612
13.654 38.385 39.797 44.449 47.680 49.545 50.357 51.187 51.612
13.685 38.218 39.926 44.227 47.680 49.581 50.172 51.132 51.529
13.715 38.200 39.908 44.320 47.514 49.434 50.080 51.224 51.455
13.746 38.218 39.834 44.172 47.551 49.267 50.264 51.114 51.326
13.776 38.191 39.852 44.449 47.624 49.249 50.135 51.040 51.317
13.807 38.228 39.834 44.504 47.495 49.341 50.227 51.021 51.409
13.837 38.107 39.871 44.375 47.310 49.212 50.117 50.892 51.307
13.868 37.997 39.797 44.061 47.329 49.138 50.006 50.763 51.308
13.898 38.025 39.630 44.135 47.347 49.120 49.914 50.763 51.150
13.929 38.043 39.797 44.172 47.292 49.193 49.821 50.781 51.068
13.959 38.098 39.908 44.117 47.273 49.046 49.895 50.744 51.123
13.990 38.172 39.982 44.246 47.347 49.046 49.987 50.837 51.077
14.020 38.246 40.055 44.264 47.310 49.046 49.950 50.874 51.105
14.051 38.218 40.074 44.283 47.292 49.120 50.117 50.707 51.086
14.081 38.108 39.945 43.987 47.292 48.917 50.172 50.855 51.197
14.112 38.071 39.871 44.061 47.310 48.898 49.914 50.929 51.132
14.142 38.163 39.963 44.061 47.243 48.991 50.080 50.744 51.031
14.173 38.144 39.963 44.080 47.292 48.917 49.895 50.800 51.067
14.203 38.098 40.055 44.098 47.292 49.101 50.024 50.873 51.114
14.233 38.246 40.184 44.393 47.292 49.101 50.061 50.984 51.178
14.264 38.329 40.092 44.393 47.347 49.065 50.061 50.763 51.067
14.294 38.329 40.203 44.246 47.366 48.935 50.117 50.671 51.095
14.325 38.347 40.203 44.190 47.255 48.954 50.061 50.560 51.012
14.355 38.274 40.388 44.265 47.292 48.843 50.080 50.707 51.095
14.386 38.246 40.314 44.227 47.292 48.750 49.950 50.597 50.994
14.416 38.089 40.221 43.969 47.292 48.917 49.840 50.597 50.966
14.447 38.107 40.036 43.988 47.353 48.806 49.895 50.449 50.874
14.477 37.960 39.963 43.821 47.255 48.584 49.637 50.394 50.726
14.508 37.831 39.908 43.840 47.163 48.640 49.618 50.338 50.652
14.538 37.997 40.018 44.006 47.273 48.529 49.729 50.431 50.698
14.569 38.071 40.110 44.024 47.292 48.566 49.747 50.541 50.828
14.599 38.052 40.166 44.080 47.292 48.566 49.747 50.541 50.948
14.630 38.061 40.147 44.209 47.070 48.695 49.784 50.597 50.874
14.660 38.126 40.258 44.172 47.089 48.750 49.840 50.523 50.892
14.691 38.163 40.406 44.154 47.292 48.714 49.766 50.412 50.902
14.721 38.107 40.277 44.265 47.366 48.750 49.747 50.541 50.957
14.752 38.181 40.461 44.301 47.329 48.695 49.858 50.541 50.994
14.782 38.135 40.369 44.246 47.329 48.677 49.784 50.578 50.929

14.813 38.071 40.277 44.265 47.310 48.695 49.803 50.560 50.837
14.843 38.080 40.203 43.988 47.310 48.603 49.636 50.246 50.717
14.874 38.034 40.258 44.117 47.347 48.677 49.710 50.191 50.846
14.904 38.089 40.314 44.172 47.255 48.695 49.821 50.523 50.874
14.934 38.071 40.406 44.098 47.255 48.714 49.914 50.578 50.818
14.965 38.061 40.240 44.098 47.163 48.750 49.784 50.596 50.828
14.995 37.960 40.203 44.153 47.144 48.695 49.821 50.523 50.846
15.026 37.951 40.203 44.037 47.126 48.621 49.858 50.652 51.031
15.056 37.979 40.295 44.061 47.310 48.806 49.895 50.633 51.012
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15.117 37.895 40.203 43.840 47.144 48.744 49.914 50.505 50.975
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15.178 37.886 39.815 43.692 47.126 48.640 49.692 50.541 50.902
15.209 37.775 39.908 43.618 47.015 48.621 49.692 50.486 50.865
15.239 37.628 39.723 43.544 46.830 48.511 49.840 50.449 50.855
15.270 37.609 39.686 43.415 46.757 48.603 49.766 50.615 50.883
15.300 37.738 39.778 43.600 46.941 48.622 49.821 50.615 50.994
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15.392 37.914 39.741 43.581 46.978 48.603 49.951 50.744 51.095
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15.483 37.849 39.723 43.563 47.033 48.695 49.895 50.615 51.151
15.514 37.886 39.741 43.563 47.015 48.695 49.877 50.726 50.994
15.544 37.932 39.741 43.600 46.905 48.714 49.895 50.652 51.040
15.575 37.920 39.667 43.748 46.997 48.695 49.840 50.744 51.021
15.605 37.905 39.612 43.655 47.052 48.566 49.809 50.652 50.957
15.635 37.951 39.667 43.637 47.070 48.603 49.710 50.652 51.021
15.666 37.849 39.797 43.563 47.089 48.474 49.766 50.689 51.012
15.696 37.794 39.797 43.471 46.830 48.307 49.563 50.486 50.892
15.727 37.797 39.840 43.434 46.646 48.492 49.508 50.375 50.948
15.757 37.914 39.834 43.563 46.738 48.418 49.821 50.467 50.883
15.788 37.895 39.686 43.563 46.757 48.511 49.803 50.431 51.049
15.818 37.840 39.612 43.507 46.861 48.511 49.636 50.375 51.021
15.849 37.720 39.870 43.507 46.757 48.363 49.643 50.498 50.911
15.879 37.794 39.926 43.304 46.664 48.289 49.747 50.375 50.957
15.910 37.914 39.520 43.452 46.627 48.252 49.544 50.542 50.948
15.940 38.052 39.686 43.489 46.738 48.363 49.600 50.504 50.911
15.971 38.006 39.760 43.673 46.701 48.381 49.655 50.504 51.031
16.001 37.960 39.741 43.526 46.609 48.400 49.618 50.523 51.104
16.032 37.858 39.667 43.323 46.461 48.270 49.471 50.541 50.994
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16.245 38.228 39.871 43.267 46.517 48.233 49.821 50.911 51.446
16.276 38.375 39.963 43.452 46.554 48.400 50.006 50.948 51.483
16.306 38.458 40.055 43.544 46.775 48.492 50.135 50.984 51.621
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16.367 38.661 40.295 43.526 46.960 48.677 50.283 51.261 51.834
16.397 38.717 40.388 43.710 46.867 48.861 50.431 51.335 51.871
16.428 38.938 40.590 43.932 47.218 48.972 50.615 51.520 52.157
16.458 39.141 40.664 43.987 47.329 48.972 50.689 51.630 52.379
16.489 39.280 40.720 44.006 47.292 49.156 50.818 51.704 52.369
16.519 39.449 40.794 44.135 47.292 49.267 50.966 51.871 52.425
16.550 39.584 40.923 44.320 47.458 49.544 51.021 51.963 52.548
16.580 39.714 41.052 44.326 47.513 49.618 51.076 52.184 52.674
16.611 39.843 41.163 44.560 47.680 49.692 51.224 52.295 52.923
16.641 39.972 41.348 44.855 47.883 50.006 51.464 52.443 52.978
16.672 40.249 41.698 44.911 48.363 50.006 51.667 52.572 53.107
16.702 40.471 41.791 45.046 48.400 50.246 51.575 52.646 53.274
16.733 40.637 41.791 45.040 48.529 50.246 51.871 52.720 53.385
16.763 40.627 41.809 45.095 48.585 50.301 51.908 52.794 53.412
16.794 40.637 41.883 45.095 48.566 50.394 51.889 52.923 53.274
16.824 40.701 41.938 45.187 48.640 50.449 51.926 52.905 53.283
16.855 40.729 42.104 45.353 48.658 50.430 51.945 52.905 53.366
16.885 40.803 41.901 45.317 48.658 50.670 52.037 52.812 53.366
16.916 40.683 41.920 45.206 48.548 50.523 52.073 52.738 53.329
16.946 40.590 41.938 45.151 48.548 50.670 51.815 52.720 53.218
16.977 40.532 41.883 45.224 48.665 50.431 51.760 52.701 53.163
17.007 40.480 41.624 45.187 48.622 50.246 51.538 52.627 53.055
17.037 40.397 41.587 45.046 48.511 50.135 51.538 52.553 52.840
17.068 40.157 41.440 44.948 48.307 50.116 51.372 52.184 52.637
17.098 39.981 41.550 44.892 48.344 49.877 51.483 51.945 52.425
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17.220 39.843 41.680 45.261 48.621 50.098 51.224 52.073 52.240
17.251 39.714 41.698 45.483 48.646 50.080 51.354 51.908 52.203
17.281 39.889 41.760 45.538 48.658 50.043 51.261 51.963 52.268
17.312 40.018 41.827 45.852 48.787 50.209 51.243 51.981 52.314
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17.373 39.981 42.326 46.166 49.175 50.431 51.501 52.129 52.387
17.403 39.991 42.234 46.314 49.267 50.541 51.557 52.110 52.379
17.434 39.566 42.178 46.554 49.212 50.338 51.409 52.055 52.148
17.464 39.151 41.791 45.907 48.917 49.932 50.837 51.667 51.705

17.495 37.664 40.794 45.649 48.510 49.230 50.172 51.058 51.151
17.525 36.871 38.966 44.745 47.514 47.551 49.009 50.024 50.163
17.556 35.052 38.541 43.526 46.221 46.572 47.901 48.658 49.037
17.586 34.452 37.895 42.640 45.409 46.184 47.310 47.717 48.040
17.617 34.424 38.006 42.603 45.391 46.572 47.698 47.698 47.837
17.647 34.837 38.929 43.544 46.000 47.273 47.957 48.178 48.511
17.678 36.077 40.018 44.394 47.144 47.883 48.640 49.286 49.037
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