Design, Operation, and Data Analysis for a Wireline Packer System in Open Boreholes, with Field-Test Results from Belvidere, Illinois

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CONVERSION FACTORS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$°F = 9/5\ (°C) + 32.$$

Degree Fahrenheit (°F) may be converted to degree Celsius (°C) by using the following equation:

$$°C = 5/9\ (°F-32).$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

A wireline-operated packer was designed for use with a standard geophysical logging system. The packer probe consists of a downhole packer inflated with water removed from the borehole by an in-line submersible pump, and a differential pressure transducer calibrated to measure the hydraulic-head difference between the zones above and below the packer. Analysis of the packer data is based on a numerical model that predicts the water levels above and below the packer for a given set of aquifer zones of specified hydraulic head and transmissivity. Various computations are used to indicate the sensitivity of the packer measurements to the hydraulic head and transmissivity contrasts between aquifer zones.

The wireline-packer probe was field tested in a series of open-bedrock boreholes in Belvidere, Illinois, at a site where vertical hydraulic-head differences are produced in a horizontally stratified aquifer by water production from an underlying aquifer. Analysis of the wireline-packer data produced estimates of hydraulic-head gradient and aquifer-zone transmissivity consistent with results from straddle-packer hydraulic tests. However, the wireline-packer data also indicated that there are significant variations of vertical hydraulic gradient with depth, and that the gradient is sharply reversed near the bottom of the boreholes. This result is consistent with upward ambient flow measured on previous occasions near the bottom of these boreholes, and has important consequences for the monitoring of ground-water flow at the study site.

INTRODUCTION

During investigations of consolidated aquifers, it is often difficult to identify the precise location of inflow to open boreholes intersecting heterogeneous aquifers where there are many possible inflow zones. The open borehole is also likely to connect zones that were previously isolated from each other, allowing for cross-flow and potential contamination of aquifers in the time period before casing and screens or packers are installed. Furthermore, it is often uncertain which zones should be isolated from each other with packers or where screens should be installed to sample specific inflow zones connected to large-scale flow paths within the regional aquifer.

In this report we describe the design, operation, and data analysis for a wireline-operated packer system for hydraulic reconnaissance in open boreholes in the period immediately after drilling. The wireline packer is designed to produce minimum disturbance to the borehole and can be operated on a standard geophysical logging wireline. Thus, the wireline packer can be conveniently included in a suite of geophysical logs run as part of the initial aquifer characterization process immediately after drilling. In addition, the report describes the field tests and results of the packer system in boreholes at Belvidere, Illinois.

DESIGN AND OPERATION OF THE WIRELINE PACKER

The wireline-packer probe was designed to provide an inflatable packer that could be used to separate a single interval of open borehole into two hydraulically isolated zones above and below a given depth. The packer used in the probe is patterned after a wireline-powered inflatable packer originally developed for the U.S. Geological Survey (Hess, 1993) as a flow concentrator for a sensitive thermal flowmeter (Hess, 1986). The pressure transducer used in the probe is a modified differential-pressure transducer. These com-

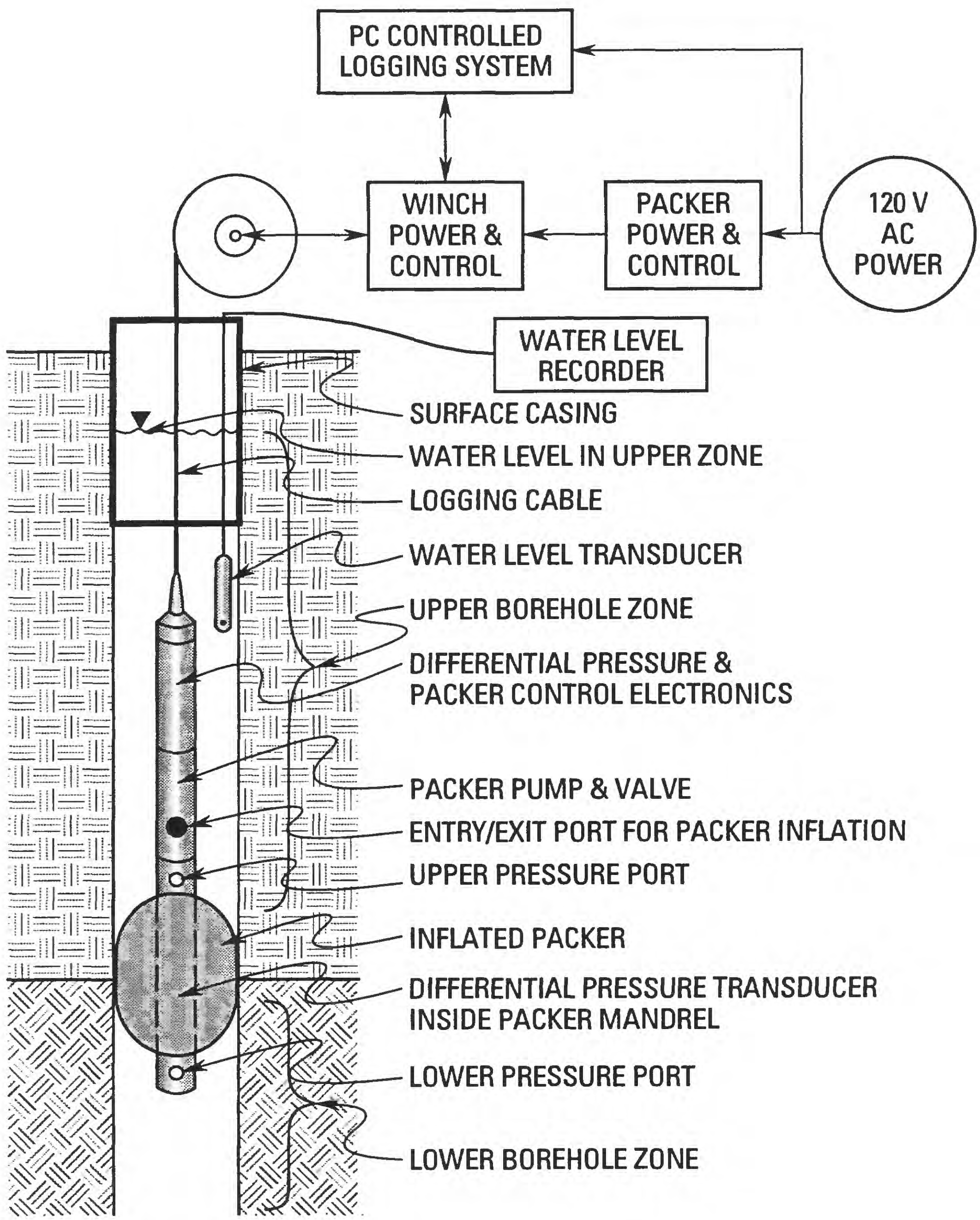

Figure 1. Wireline-packer system for water-level measurement.

ponents were combined in a logging probe that can be operated through a single-conductor logging cable (fig. 1). The logging system used with the probe for the field part of this study includes the differential-pressure/packer probe, an uphole packer power and control module, a wire-line logger consisting of a winch, logging cable, and winch power and control unit; a PC-controlled logging and recording system; a separate water-level transducer and recording system; and an AC power source.

The packer is inflated by withdrawing water from the borehole using a submersible pump mounted within the probe. This process results in a much smaller disturbance to the hydraulic environment in the borehole than that produced when the packer is inflated using pressurized gas from the surface (where a volume of water equal to the entire volume of the inflating packer is displaced within the borehole).

The wireline packer is designed with a sensitive differential transducer (Druck, 10 pounds-per-square-inch rated) calibrated in feet of water-level difference between the isolated zones above and below the packer. This arrangement provides maximum sensitivity to water-level differences while accommodating large differences in hydrostatic loading associated with variations in depth settings of hundreds or even thousands of feet. A similar sensitive measurement of water level in the borehole above the packer can be made using a transducer installed just below the largest expected changes in water level, and defined with respect to a reference point at the surface. These two measurements can then be used to infer the water levels in the two open-borehole zones above and below the packer at each measurement station.

The differential transducer is mounted inside the packer portion of the probe. One port of the differential transducer is vented to the water above the packer, and the other transducer port is vented to the water below the packer. Thus, the pressure transducer measures the static hydraulic-head difference between the zones above and below the measurement station when a borehole is sealed by an inflated packer. Electronics within the probe transform the output of the differential-pressure transducer into a format suitable for transmission through the logging cable to the surface. The logging system at the surface scales and records the pressure information and other logging parameters as a function of time after each packer inflation. The submersible pump incorporated in the logging probe is controlled by the packer power and control unit at the surface. Packer pressure is controlled by the logging operator by regulating the current to the pump.

The probe is modular in design to allow other configurations, such as multiple packers or insertion of a flow measurement device in the center of the probe. Therefore, one or more packers and pressure transducers may be added to the probe, allowing its use as a straddle packer. A borehole flowmeter can be installed in place of the differential-pressure transducer. In such a configuration, the inflated packer acts as a flow concentrator increasing the sensitivity of flowmeters such as the heat-pulse (Hess, 1986; 1990) or electromagnetic (Molz and Young, 1993) flowmeters. Thus, a single logging probe could be used as both flowmeter and wireline packer by a simple change of module.

Borehole measurements are made with the probe stationed at a given depth. Before the packer is inflated, there is no differential pressure between the zones above and below the probe. Any small pressure differences registered by the transducer result from electronic drift and from response to pressure changes as the probe is moved along the borehole. These errors are expected to be negligible in most situations. After the packer is inflated, the differential-pressure transducer measures the pressure (hydraulic-head) difference between the borehole zones above and below the packer. The water-level transducer and recorder measure the change in water-level in the open-borehole zone above the packer after packer inflation. In general, it may take some time for the borehole pressure to stabilize after packer inflation. During this period, differential transducer response in the probe and absolute transducer response in the upper zone are monitored. The measurements are continued until a steady state is reached, as indicated by steady pressure readings from the transducer (fig. 2). In figure 2, the reference for the upper zone water level is defined as zero. The changes in water level that are shown before packer inflation starts represent a response to packer deflation after the previous measurement. The offset from zero on the differential transducer response in figure 2 represents drift in transducer response with time. This baseline transducer response (taken as the average of open-hole response measured before inflation and after deflation) is subtracted from the final steady reading given by the differential transducer.

The data collected with the packer and two transducers provides the steady-state water-level difference across the packer, and the upper zone water level at each packer setting. In conformance with typical mea-

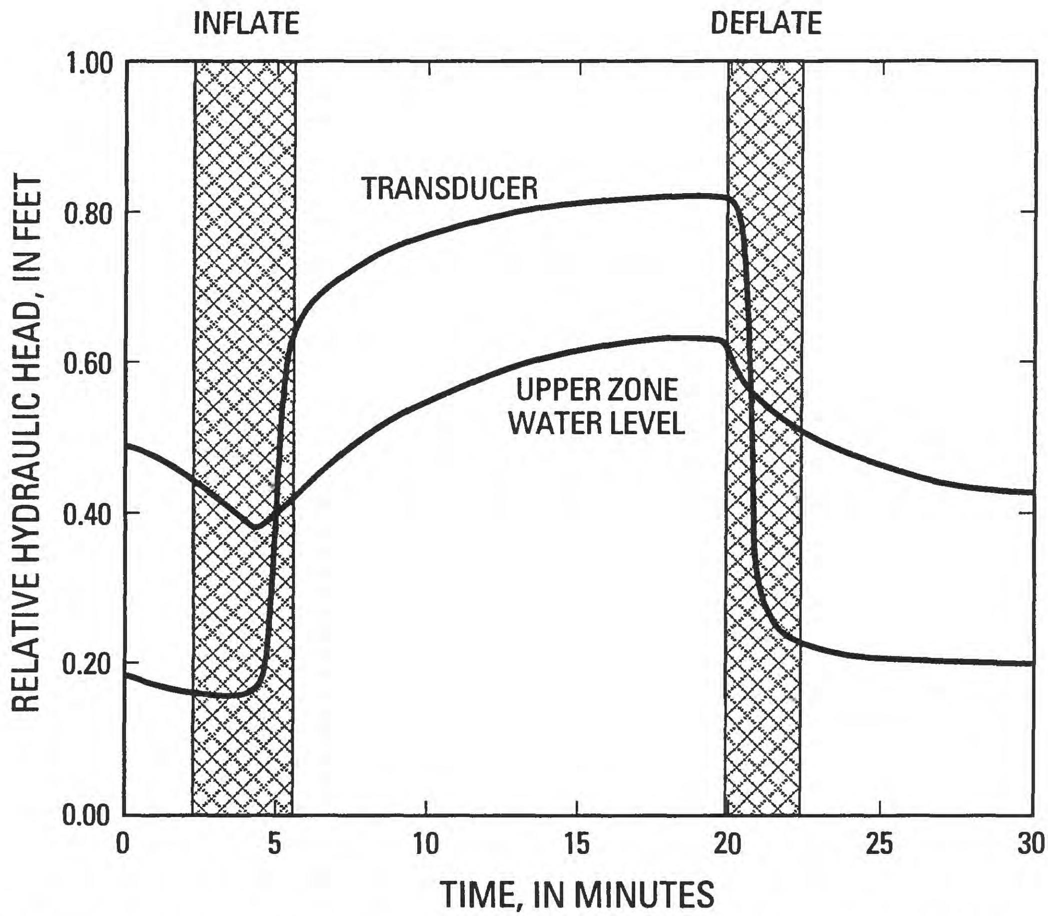

Figure 2. Transient changes in water level recorded by differential transducer and upper water-level monitoring system during a measurement cycle at the 115-foot measurement station in borehole T-3 at the Belvidere, Illinois, site.

surement conventions, we define the water level in the upper zone in feet below the top of casing. The differential transducer provides a positive differential when the water level in the upper zone is above that in the lower zone. Thus, the water level in the lower zone is determined by subtracting the differential from the measured water level in the upper zone. Accordingly, final measurement output is given as paired water-level depths below a surface reference point.

A few comments can be made about the use of a single packer. It might appear advantageous to isolate a very short test interval with a straddle-packer system to obtain a direct measurement of the hydraulic head in a specific zone. One then has to make a large number of measurements to cover a borehole with, for example, a 5-foot straddle-packer spacing. If we make the interval any longer than that, the logging tool is too big for practical use. With the single packer, we can make coarsely spaced measurements, and then rule out long intervals where there is no effective difference between measurements. Each of these measurements involves a pressure response time determined by the most rapidly responding zones in the borehole. In contrast, straddle-packer isolation and testing of individual zones would involve the testing of many non-conductive zones. Each such test might require many hours. The efficiency of the single packer method in avoiding the testing of most non-responsive intervals is obvious.

ANALYSIS OF PACKER DATA

Description of Numerical Model

The steady-state flow (q) into an interval of borehole from a large distance *R* is given by the equation (Davis and DeWiest, 1966; fig. 3):

$$q = 2\pi T(h - h_0)\ln\left(\frac{R}{r}\right) \qquad (1)$$

(1) where *T* is the zone transmissivity, *h* is the far-field water level at the "outer edge" of the zone, h_0 is the water level in the borehole, and *r* is the borehole radius. If there are N zones communicating with each other along a section of open borehole, then the flow in each such zone (q_k) is given by:

$$q_k = 2\pi T_k(h_k - h_0)\ln\left(\frac{R}{r}\right) \quad k = 1, 2, 3, \ldots N \qquad (2)$$

where the hydraulic head in each zone (h_k) may be different from that in the other zones, and from the water level in the borehole. Such a situation allows steady flow along the borehole, producing the flow needed to support the observed head differences between zones. When the borehole is shut in so that *N* individual zones are open to the borehole, but there is no net flow into or out of the borehole, then the sum of all these inflows must be zero. This requirement insures that the hydraulic head in the shut-in interval is equal to the transmissivity-weighted average of the heads in the individual zones.

$$\sum q_k = \sum\left(2\pi T_k(h_k - h_0)\ln\left(\frac{R}{r}\right)\right) = 0$$

$$\text{or} \qquad (3)$$

$$\sum T_k h_k = h_0 \sum T_k \text{ and } h_0 = \frac{\sum T_k h_k}{\sum T_k}.$$

Therefore, if we number packer stations sequentially from the bottom of the borehole and assume that there are a total of *N* inflow or outflow zones, we can relate the measurements made at each packer setting to the T_k and h_k of the zones above and below the packer. We use the convention that setting *k* denotes packer position below the k^{th} producing zone. Then there are a total of N+1 possible packer positions (N-1 positions between the *N* zones, and one each above and below all of the zones). At each of these positions, we can make two measurements, the water level above and below the packer. This is a total of 2(N+1) data points. However, four of these measurements are not independently derived. The two packer settings that are either above or below all of the producing zones provide two pairs of measurements (water level above and below the packer) that are not independent. Two of these four data points (one in the lower zone when the packer is below all producing zones, and one in the upper zone when the packer is above all producing zones) are meaningless. The other two give the same number: the open-hole water level. Thus, there are a total of 2(N+1)-4 = 2N-2 independent measurements, plus the open-hole water level (best measured before disturbing the well with the packer tool) for a total of 2N-1 data points.

The number of measurements provided by the packer tool can be compared to the number of unknowns we need to solve for in describing the aquifer. Each producing zone is described (at steady state)

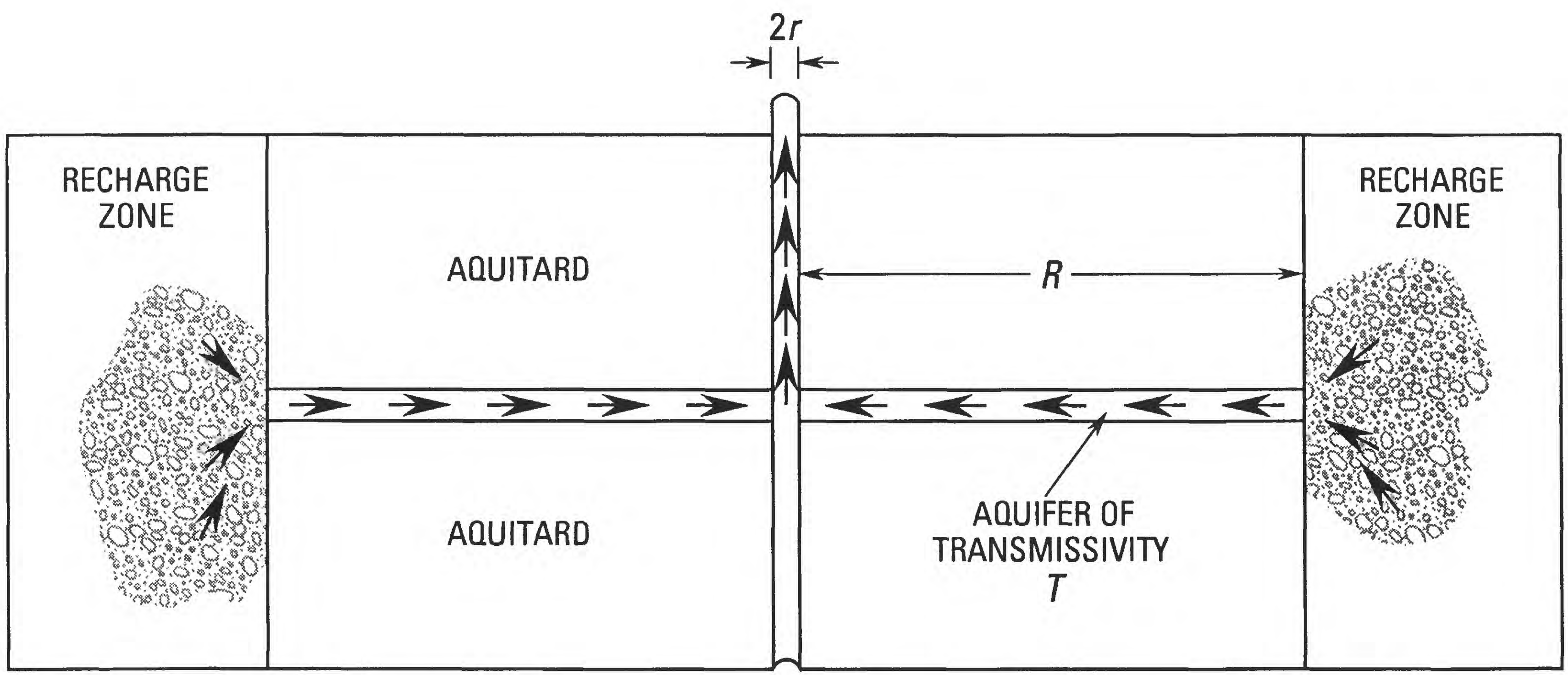

Figure 3. Steady radical flow along a confined aquifer of transmissivity *T* from a recharge zone located at a radical distance *R* from a borehole of radius *r*.

by two parameters: zone transmissivity (T_k) and the shut-in far-field hydraulic head (h_k). Therefore, we have enough measurements to solve for all but one of these. The problem is formulated so as to solve for all of the hydraulic heads (h_k) and the T_k values as a multiple of T_1. In the analysis, we use a forward model to predict the water levels above and below each packer setting as a function of specified number of zones (N), the hydraulic head in each zone (h_k), and the T_k as multiples of a reference value.

In the forward model, we take the water level in the lower zone (WLB_k) as follows:

WLB_1 - meaningless (dead zone below all inflow)

$WLB_2 = h_1$

$$WLB_3 = \frac{T_1 h_1 + T_2 h_2}{T_1 + T_2} \tag{4A}$$

$$WLB_{N+1} = \frac{T_1 h_1 + T_2 h_2 + \ldots + T_N h_N}{T_1 + T_2 + \ldots + T_N}$$ - open-hole water level.

A similar set of equations applies for the water level above each packer setting, except that the calculations are performed from the top of the borehole down:

WLA_{N+1} - meaningless (water isolated from borehole in the zone above all inflow zones)

$WLA_N = h_N$

$$WLA_{N-1} = \frac{T_N h_N + T_{N-1} h_{N-1}}{T_N + T_{N-1}} \tag{4B}$$

$$WLA_1 = \frac{T_N h_N + T_{N-1} h_{N-1} + \ldots + T_1 h_1}{T_N + T_{N-1} + \ldots + T_1}$$ - open-hole water level.

These equations are used to compute the sets of packer measurements. The model inputs can then be adjusted until the predicted water levels are reasonably close to the measured values. The numerical models used to fit data described in this report were computed using a forward modeling program that eventually could be installed as part of the data processing capability of the wireline-packer logging system.

The degree to which the model fits the data is expressed as the mean square difference between the computed water levels and the measured water levels. If we define $WLAM_i$ and $WLBM_i$ as the measured water levels above and below packer station index *i*, then the root square difference (D) between data and model predictions is given by:

$$D^2 = (WLAM_1 - WLA_1)^2 + \sum_{i=2}^{N} \left((WLAM_i - WLA_i)^2 + (WLBM_i - WLB_i)^2 \right). \tag{5A}$$

We then define *A* as the maximum difference between water levels measured during the packer experiment. *A* will sometimes be the difference between the water level above the packer in the uppermost setting (WLA_N) and the water level below the packer in the next to lowermost setting (WLB_2). In other situations, the water levels may not increase or decrease systematically with depth between these uppermost and lowermost settings. In such situations, *A* is determined by identifying the maximum and minimum water levels within the set of data. Once *A* is determined, the average error (E) in the fit of model predictions to the data is given by:

$$E = \frac{D}{(2N-1)A} \tag{5B}$$

Graphical Representation of Data

The model computations described by equations 1-5 suggest a general scheme for modeling data obtained with the wireline packer. Because the packer is inflated for each measurement, the data are obtained at discrete depth stations. In field applications, the wireline packer is used in conjunction with other geophysical logs. The packer measurement stations are determined by inspection of other logs to indicate possible inflow points and to identify places where the packer can effectively seat against a smooth borehole wall. We expect that there will be no difference in WLA or WLB measurements whenever the packer is set either above or below all of the inflow zones. In that situation, one side of the differential transducer is open to all of the producing zones and registers the open-hole water level. The other side of the differential transducer is not connected to any producing zone and so remains fixed at the last water level to which it was exposed before seating of the packer. That water level is assumed to be the same open-hole water level. Thus, both wireline packer measurements (WLA and WLB) would coincide with the open-hole water level at all depth stations above and below the producing zones. In the intervening interval, the water levels above and below the packer may differ, and this pattern of separation of the WLA and WLB data gives information about the transmissivity and hydraulic heads of the individual producing zones.

We propose that the wireline data be presented as indicated in figure 4. The measurements are given as discrete data points at specific depth stations. At least one and possibly several such data points are obtained at depth stations between each suspected inflow point. The data points are then fit to a series of straight-line segments coinciding with the depth intervals between producing zones. The straight line segments are joined by either discontinuous "jumps" for discrete bedding plane and fracture inflow zones, or by "ramps" coinciding with permeable bed inflow zones as shown in figure 4. The numerical interpretation consists of finding the best model fit of the h_k and T_k for *N* possible inflow zones. The model predicts the water levels given by the straight line segments in figure 4. An effective software graphics system would overlay predicted line segments on the data as a visual cue in data analysis, allowing the analysis to identify the model profiles for WLA and WLB that match the data.

SENSITIVITY ANALYSIS

The simplest example of wireline-packer measurements would be in a borehole connecting two otherwise isolated permeable zones. However, this is an oversimplified situation because the single packer isolates the two zones whenever the packer is set at a depth between the locations where these zones intersect the borehole. The water-level measurements above and below the packer would give direct measurements of the water levels in the two zones:

$$WLA = h_2 \qquad WLB = h_1 \tag{6A}$$

where *WLA* and *WLB* are the water levels measured above and below the packer whenever it is set in the interval between the two zones. The ratio of the transmissivity values for the two zones would be given by:

$$\frac{T_2}{T_1} = \frac{WLA - WL}{WL - WLB} \tag{7}$$

where *WL* denotes the water level in the open borehole.

A more challenging application of the packer data occurs when there are three or more zones intersecting the borehole. In the three-producing-zone situation, the water levels in the uppermost and lowermost zones are still directly measured by the wireline packer:

$$WLB_2 = h_1 \qquad WLA_3 = h_3 \tag{6B}$$

The sensitivity of the measured *WLA* and *WLB* values to the intermediate parameters (h_2 and T_2) is investigated by computing the profiles of WLA and WLB that would be measured under various conditions (fig. 5). These simple examples are presented as profiles of WLA and WLB as a function of depth along the borehole for effective comparison with other logs. The values are constant over intervals where there is no inflow to the borehole, and jump abruptly in the intervals where water-producing features, indicated as bedding plane fractures, intersect the borehole.

Sensitivity computations show that as long as the intermediate fracture has a transmissivity approximately equal to that of the other two zones (fig. 5A), the presence of a water-producing fracture is always indicated by the water-level data. The "step" in the water-level profiles is always obvious in the data whether h_2 is intermediate to the other two values, or equal to either one (fig. 5A). The "step" in the profile shifts from one side to the other, but always occurs in the data.

However, when the transmissivity of the intermediate fracture (T_2) becomes more than one order of magnitude smaller than the other two T values, the step in the profile becomes very small. The results in figure 5B indicate that the presence of the intermediate fracture would probably not be detected if the T of the intermediate fracture is more than one order of magnitude less

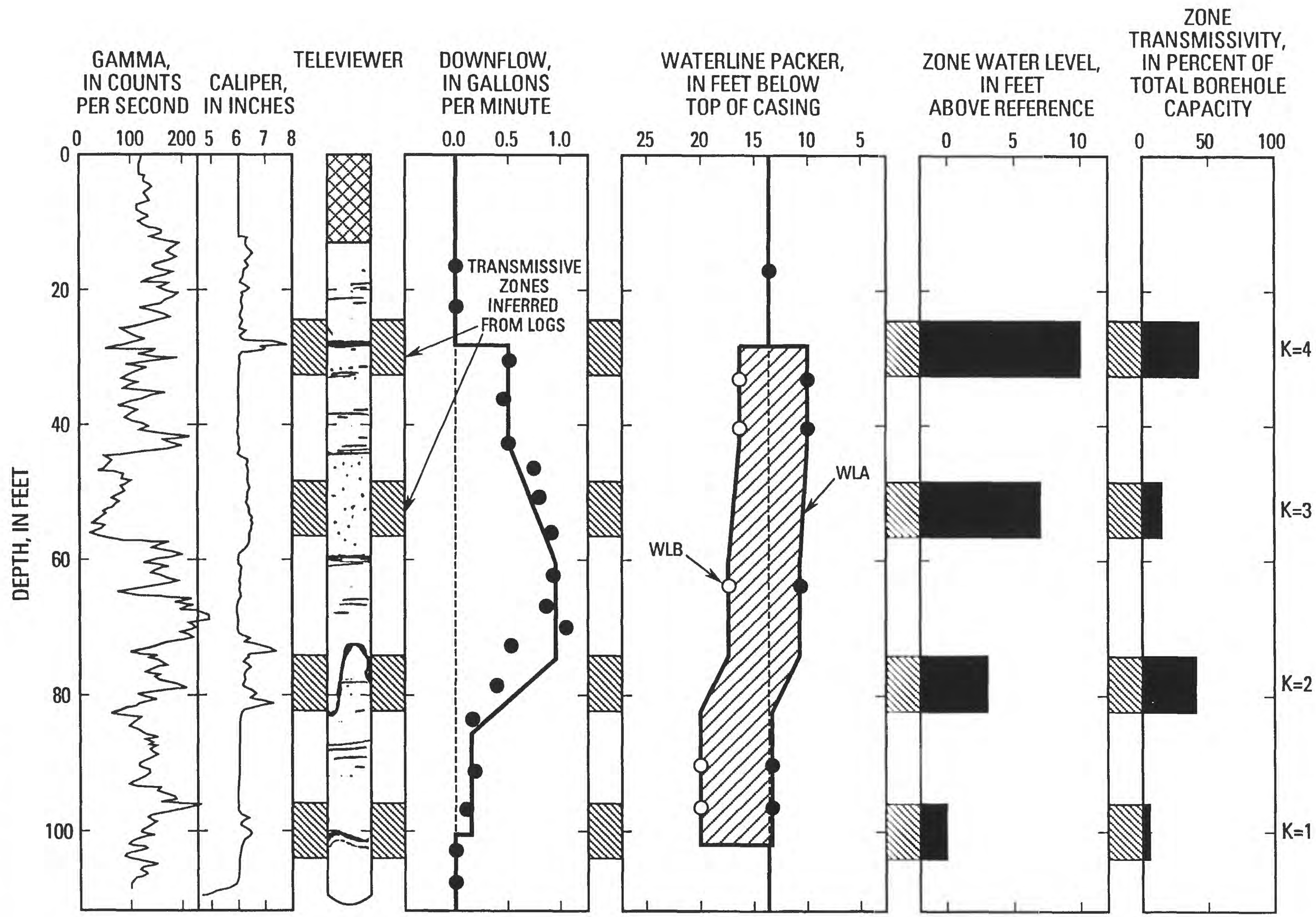

Figure 4. Measured water-level data for the zones above and below the inflated packer and selected well logs; profiles are generated by fitting straight line segments for WLA and WLB between inflow zones inferred from inspection of other borehole data.

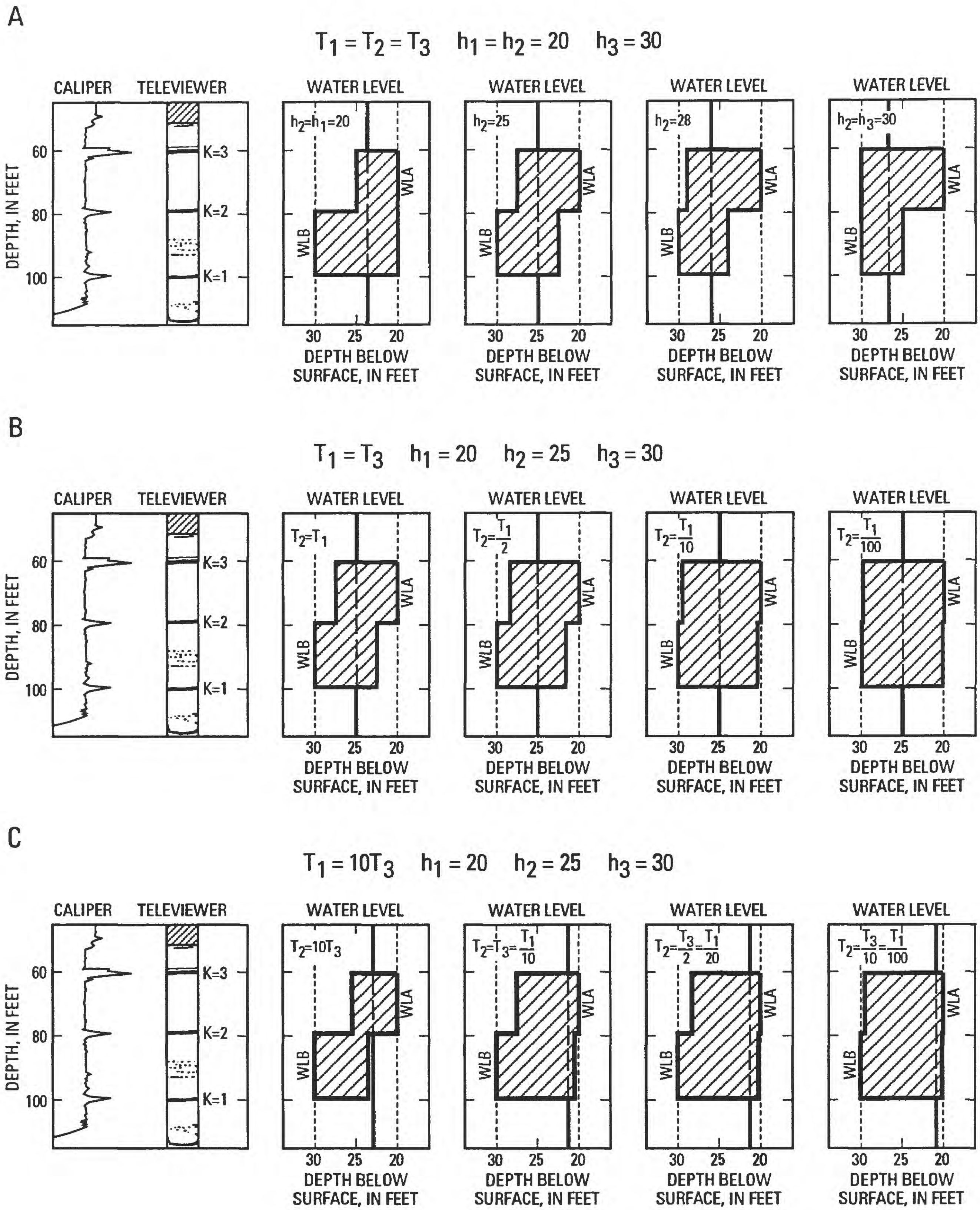

Figure 5. Effects of variations in transmissivity (T) and hydraulic head (h) on measured water levels from a hypothetical 3-inflow zone interpretation problem: A) all T_k and h_k are held constant except for h_2; B) all T_k and h_k are held constant except for T_2; and C) similar to B except that T_1 is made very large.

than the T of the other two fractures. In some situations, one highly transmissive fracture presents a T value orders of magnitude greater than all of the other producing zones (fig. 5C). In that situation, the presence of one such highly transmissive fracture does not preclude the detection of other fractures.

The "masking" of relatively tight fractures only occurs when the low transmissive fracture lies between two more transmissive fractures. In that situation, the measured water levels always involve the interaction of one or more transmissive fractures with the less transmissive fracture, and there is no opportunity to measure the hydraulic properties of the less transmissive fracture independent of the more transmissive fractures. When a less transmissive fracture lies between the more transmissive fracture or fractures and the bottom of the borehole, the packer can isolate the interval with the less transmissive fracture from that intersected by one or more highly transmissive fractures. When less transmissive fractures lie between two or more such highly transmissive fractures, such isolation is not possible without using multiple packers.

WIRELINE-PACKER FIELD TESTS

The Belvidere, Illinois, site was selected for field tests of the wireline packer for several reasons. The site has an array of several open boreholes known to connect zones of different hydraulic head and the distribution of ambient flow in the boreholes has been measured on several different occasions. The head differences driving the measured flow have been measured in a few intervals isolated with straddle packers as part of a conventional hydraulic-testing program. Although water levels were observed to fluctuate over time as a result of variations in water production from underlying aquifers by adjacent supply wells, these data give independent information on the approximate magnitude of water-level differences driving the flow along the boreholes. The water-producing zones in the Belvidere boreholes consist of at least two nearly horizontal permeable beds intersecting all seven boreholes, a shallow nearly horizontal bedding-plane fracture in three boreholes, and a nearly vertical fracture in two others. Thus, the Belvidere borehole array provides examples of three different classes of producing zones. Because this site is contaminated, water could not be produced or injected over periods long enough to run quasi-steady flow measurements under any condition other than ambient. At the same time, short interval straddle-packer tests could not be made over the entire length of all boreholes. For these reasons, there are enough data available at this site to provide corroboration of results obtained with the wireline packer, while the analysis of the data described here has the potential to further contribute to the understanding of hydraulic conditions at the Belvidere site.

Before starting the field tests, the wireline packer data calibration in actual water-level rise was checked in the field by comparing transducer difference values with water-level rise given by the water-level transducer when water was added to the casing with the packer stationed just below static water level (fig. 6). The water-level transducer calibration was verified by checking water-level increases with an electric tape during each of these experiments. These data demonstrate that the differential transducer values read from responses such as that in figure 2 need to be multiplied by a correction factor of 1.06. Such corrected values have been used to give the water level below the packer for the Belvidere water-level data. These data are used to compute the values of WLB_k used in the analysis at the Belvidere site.

The wireline packer was tested in three boreholes at the Belvidere site: boreholes T-1, T-3, and T-6. These three boreholes were selected to represent the three different configurations of intersected producing zones at the site: 1) boreholes intersecting only the nearly horizontal permeable beds (T-3); 2) boreholes intersecting those beds and a nearly vertical fracture (T-1); and 3) boreholes intersecting the permeable beds and a nearly horizontal bedding-plane fracture (T-6).

Measured Water Levels

The steady-state water levels measured above and below each depth station after packer inflation are listed in table 1. Significant differences in water levels between zones above and below the packer were detected at almost all of the measurement stations where data were recorded in these three boreholes (figs. 7-9). The "steps" in the WLA and WLB measurements clearly coincide with the major fractures in boreholes T-1 and T-6, and with various horizontal beds in all three boreholes. Additional repeat measurements were made at a few depth stations in the boreholes, demonstrating the reproducibility of the measurements. These measurements were repeatable, even when the

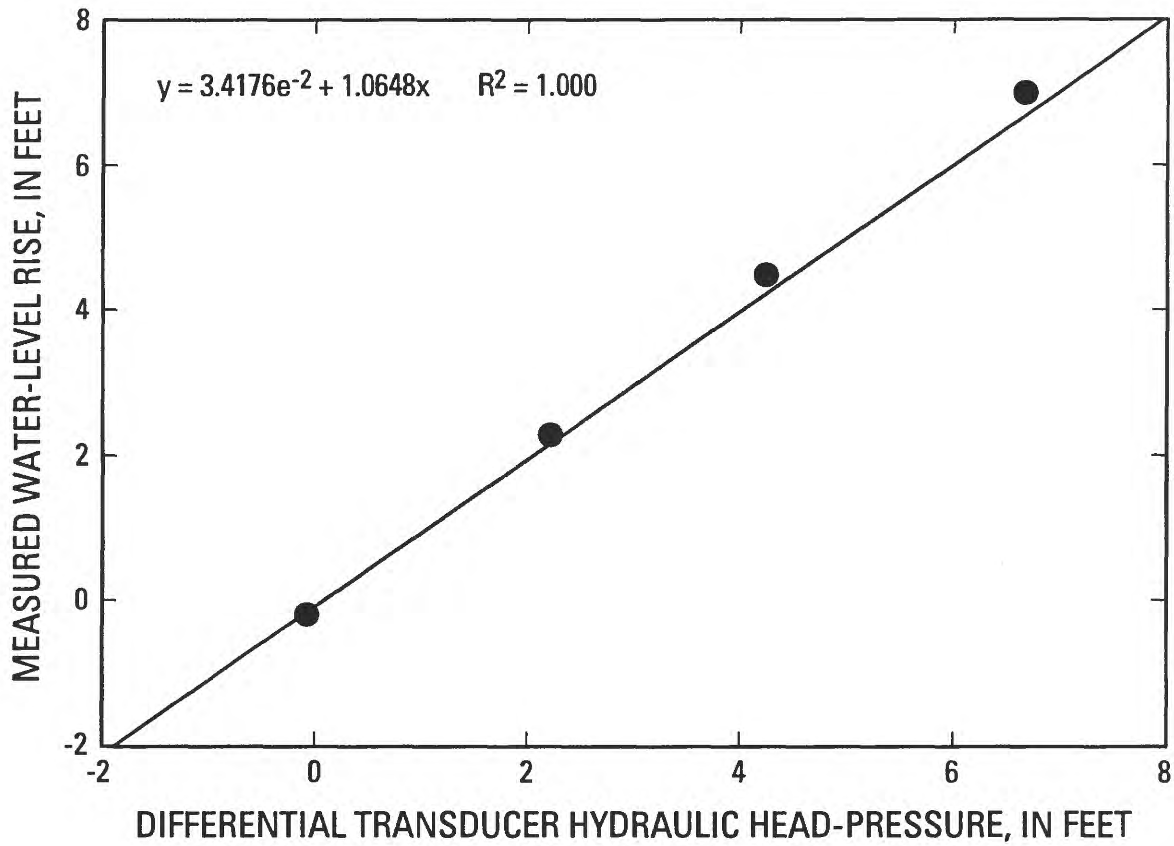

Figure 6. Measured water-level rise and differential transducer hydraulic-head pressure when the packer is inflated below water level in a casing and water is added manually to the top of casing.

TABLE 1. Wireline-packer test results from Belvedere, Illinois, boreholes

Depth in feet below top of casing	Differential transducer readings in feet				Net difference in feet	Corrected difference in feet	Water level in feet below top of casing	
	Before	After	Average	Packed			Above	Below
				Borehole T-1				
Open-hole water level							22.30	
40	---	0.18	0.18	-0.02	-0.20	-0.21	22.45	22.24
40	0.40	---	0.40	0.22	-0.18	-0.19	22.45	22.26
60	0.14	0.20	0.17	0.02	-0.15	-0.16	22.40	22.24
60	0.05	0.09	0.07	-0.05	-0.12	-0.13	22.39	22.26
90	0.20	0.20	0.20	0.44	0.24	0.25	22.26	22.51
90	0.33	0.41	0.37	0.70	0.33	0.35	22.25	22.60
90	0.34	0.29	0.32	0.58	0.26	0.28	22.24	22.52
115	0.38	0.43	0.41	0.88	0.47	0.50	22.24	22.74
140	0.39	0.41	0.40	0.99	0.59	0.63	22.23	22.86
170	0.39	0.40	0.40	0.00	0.60	0.64	22.31	22.95
200	0.39	0.49	0.44	0.63	0.19	0.20	22.26	22.46
				Borehole T-3				
Open-hole water level							22.67	
60	0.05	0.11	0.08	0.53	0.45	0.48	22.30	22.78
90	0.27	0.28	0.28	0.68	0.40	0.42	22.34	22.76
115	0.37	0.40	0.39	1.02	0.63	0.67	22.38	23.05
140	0.38	0.43	0.41	1.17	0.76	0.81	22.38	23.19
				Borehole T-6				
Open-hole water level							22.28	
32	0.15	0.14	0.15	-0.06	-0.21	-0.22	22.46	22.24
60	0.15	0.17	0.16	0.55	0.39	0.41	22.29	22.70
90	0.17	0.25	0.21	0.57	0.36	0.38	22.29	22.67
115	0.38	0.41	0.40	0.98	0.58	0.62	22.29	22.91
115	0.35	0.44	0.40	0.94	0.54	0.57	22.28	22.85
140	0.40	0.44	0.42	1.44	1.02	1.08	22.28	23.36
160	0.41	0.44	0.42	1.73	1.31	1.39	22.29	23.68
180	0.40	0.42	0.41	0.58	0.17	0.18	22.29	22.47

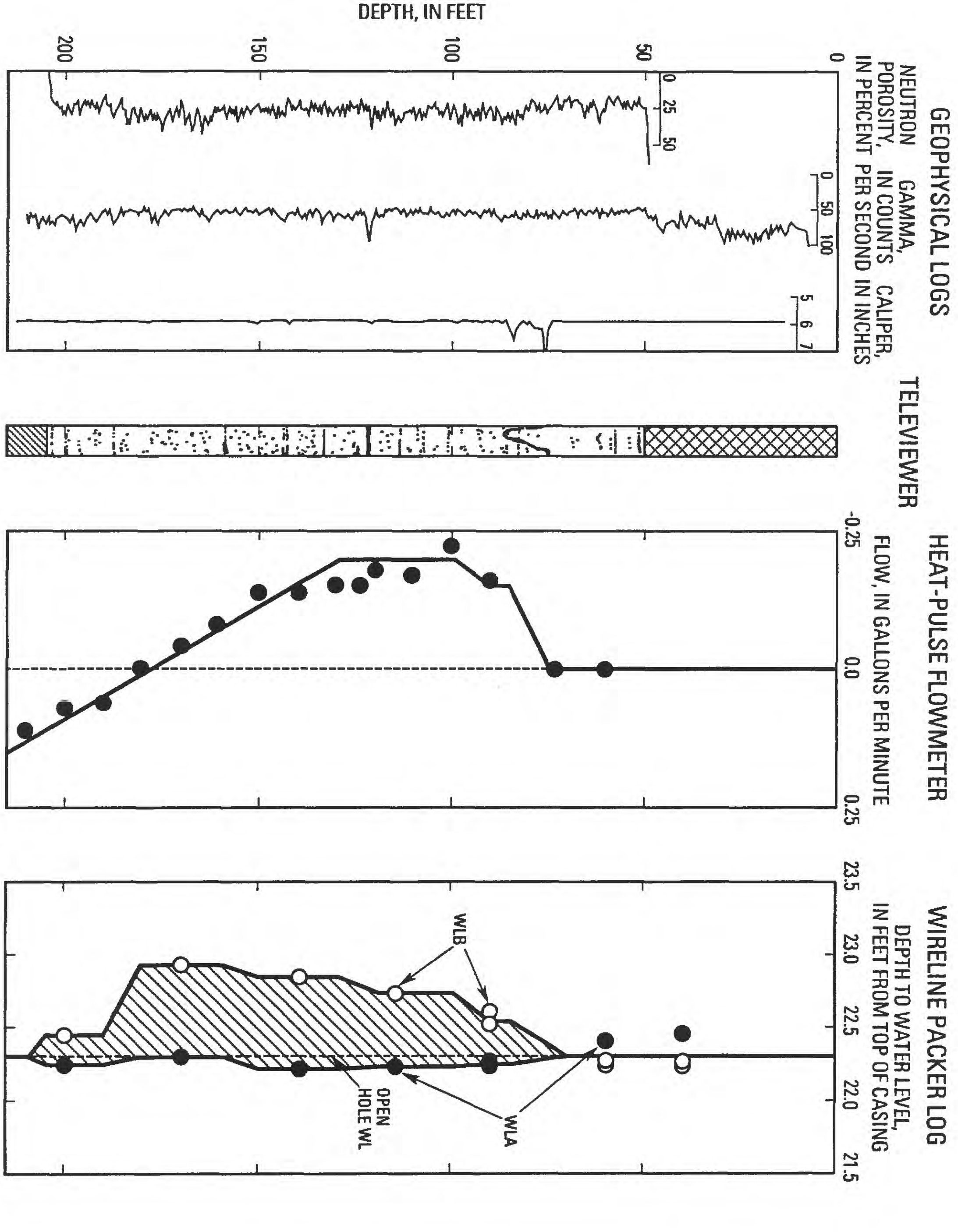

Figure 7. Water levels measured in borehole T-1 with the wireline packer, borehole flow measured under ambient conditions, and selected geophysical logs at the Belvidere, Illinois, site.

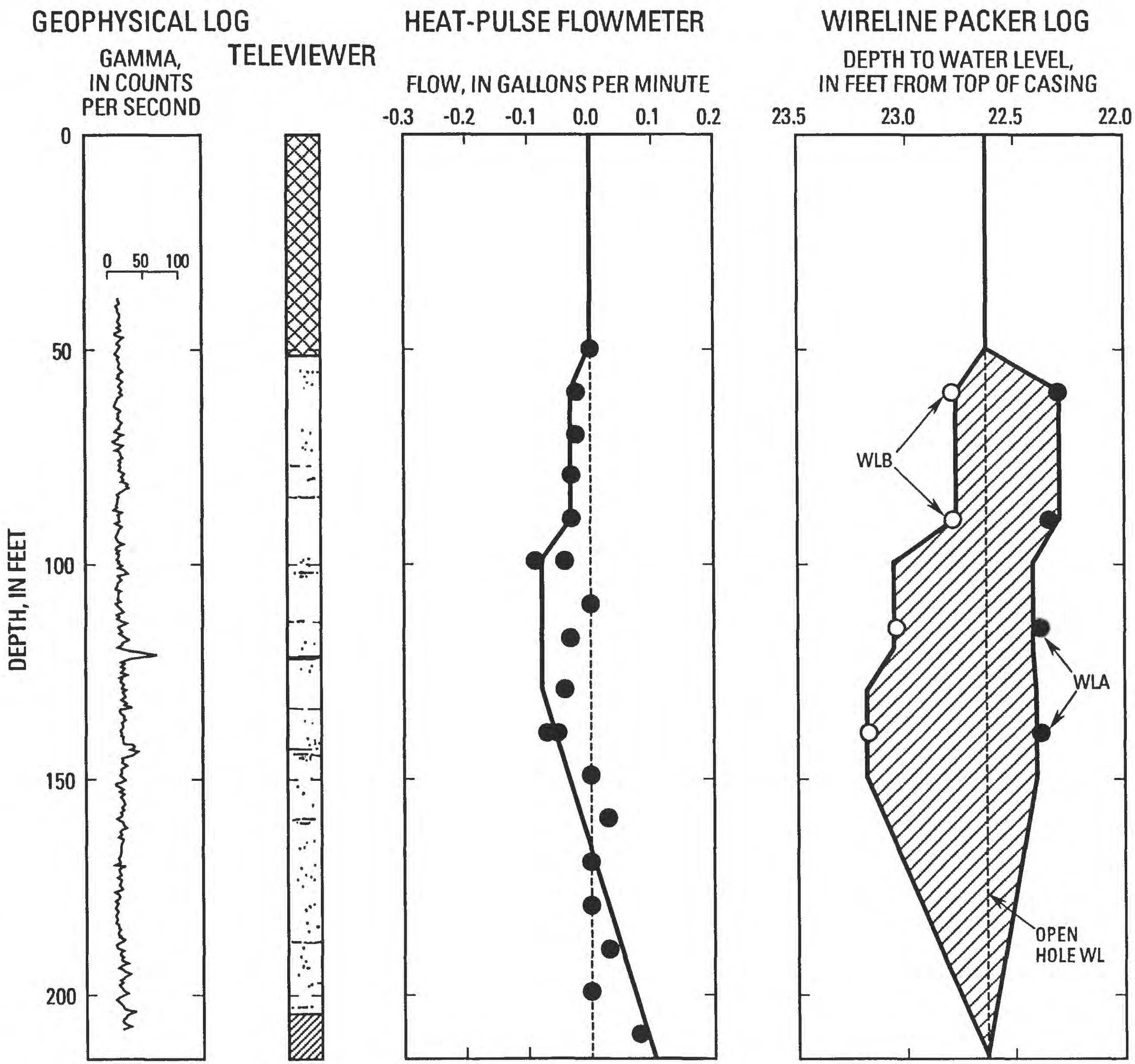

Figure 8. Water levels measured in borehole T-3 with the wireline packer, borehole flow measured under ambient conditions, and selected geophysical logs at the Belvidere, Illinois, site.

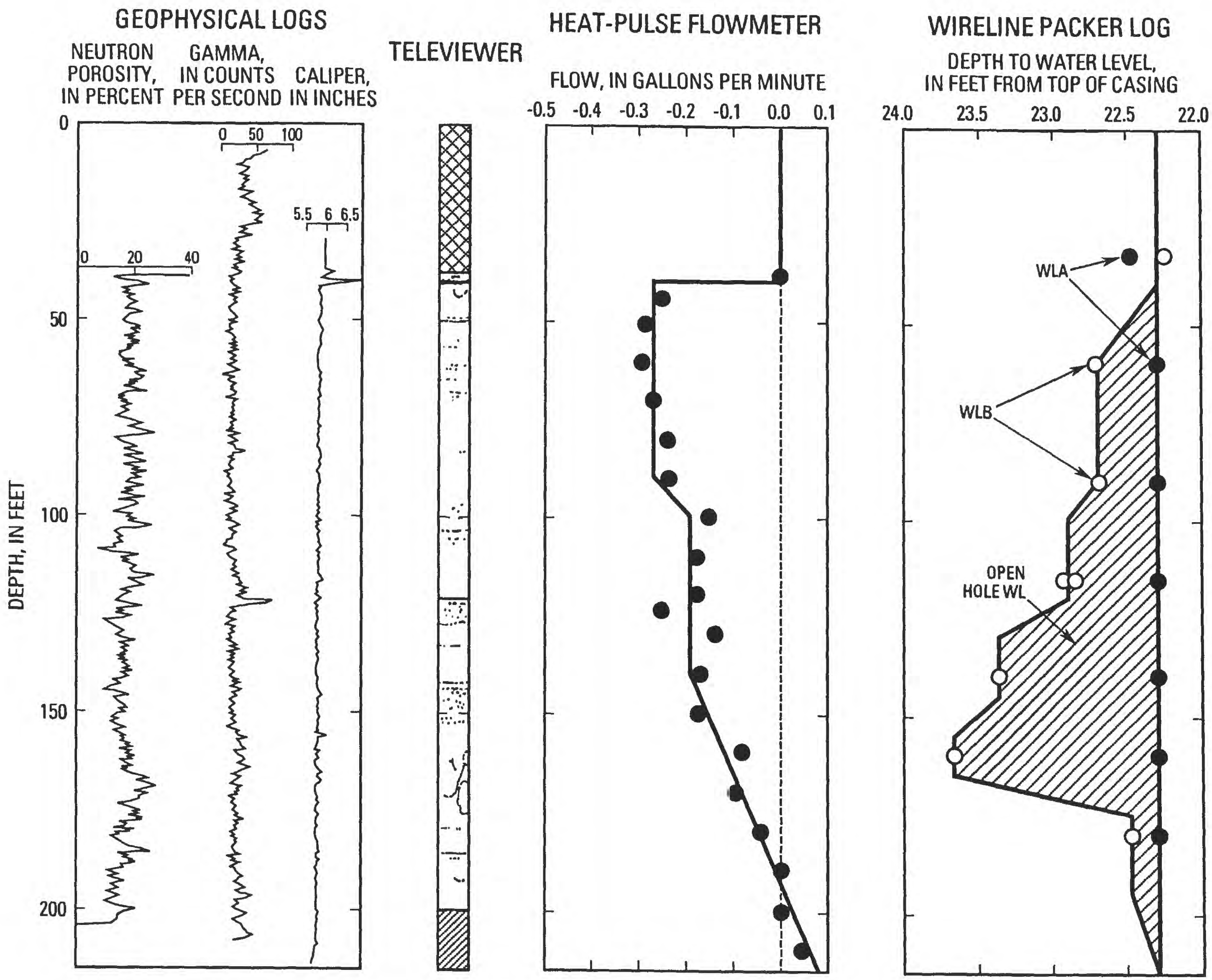

Figure 9. Water levels measured in borehole T-6 with the wireline packer, borehole flow measured under ambient conditions, and selected geophysical logs at the Belvidere, Illinois, site.

packer had been deflated and moved to other depth stations in the period between measurements.

The only anomalous measurements were made in casing just below water level. In these measurements, there was no possible source of inflow or outflow above the packer. In theory, water levels above and below the packer should both equal the water level in the open borehole. Instead, the water level in the zone above the packer fell to a small fraction of a foot lower than that in the zone below the packer, as indicated by the differential transducer response. This result is attributed to the continued withdrawal of water from the borehole by the packer pump after the packer made contact with the borehole wall. As shown in figure 1, the inlet port for the pump used to inflate the packer is located above the packer. Therefore, the water withdrawn from the borehole to inflate the packer comes from the zone above the packer. Water withdrawn from the upper zone cannot be replaced after the packer makes contact with the borehole wall whenever the packer is stationed above all possible inflow zones. We conclude that the separation of the measured WLA and WLB data for the uppermost two points in figure 7 and the uppermost point in figure 9 represent such a response to packer inflation and are not a real indication of a difference in aquifer hydraulic head in the zones above and below the packer. This conclusion is obvious for the two data points where the measurement was made in the lower part of casing. The second pair of wireline-packer data points from the top in figure 7 were obtained with the packer stationed in the open borehole about 10 feet below the bottom of casing. Measured water-level response at this point also indicates that there is no inflow to the borehole in the interval of open borehole between that measurement station and the bottom of casing.

Model Results

The water levels obtained at various depth stations in the three Belvidere boreholes are fit to model parameters that give a reasonable agreement with the data points (all with less than 5% error) in figure 10. The parameters associated with these model fits to the data are summarized in table 2. The water-level measurements are assumed to have an error of ±0.05 feet, and all model-generated water levels match the measurements within this assumed error.

The relative distribution of hydraulic head and transmissivity in each identified producing zone are given in figure 12. To test the sensitivity of the model to aquifer parameters, we compared the fit of model predictions for slightly different parameters. These different models are tested using the borehole T-3 data where the 4-zone model is the simplest among the three boreholes. In the first such calculation (model A in fig. 11), we use slightly different hydraulic-head values, making the intermediate aquifer zone heads (k_2 and k_3) more evenly intermediate between the values for the k_1 and k_4 zones than the values used in the best fit model. The model A parameters clearly do not fit the data as well as the best fit model, strongly supporting the conclusion that the hydraulic heads in the aquifer zones do not decrease evenly with depth.

In a second calculation (model B in fig. 11), we change the relative transmissivity values of the intermediate zones (T_2 and T_3) only slightly from those of the best fit model. The model predictions based on these slightly different transmissivity values do not fit the measured water levels nearly as well as the best fit model, even though the open-hole water level predicted by model B is not as far from the measured open-hole water level as that predicted by model A. Again, we conclude that the model fits in figure 10 are reasonably sensitive to the relative distribution of transmissivity along the borehole.

Interpretation of Results

The distribution of hydraulic head and transmissivity with depth inferred from the wireline-packer data (fig. 12) are consistent with other interpretations of data from the Belvidere boreholes (Paillet, 1997) and with the distribution of transmissivity determined from slug tests in isolated zones (R.T. Kay, U.S. Geological Survey, written commun., 1998). The wireline-packer data indicate that hydraulic head decreases with depth in all three boreholes studied. The wireline-packer data interpretation also agrees with Paillet (1997) in assigning the bedding-plane fracture (borehole T-6) and vertical fracture (borehole T-1) aquifers transmissivity values more than an order of magnitude greater than those of the horizontal beds intersected by the boreholes. The model data listed in table 2 indicate a relative transmissivity for the bedding plane and vertical fracture about 30 times greater than the transmissivity

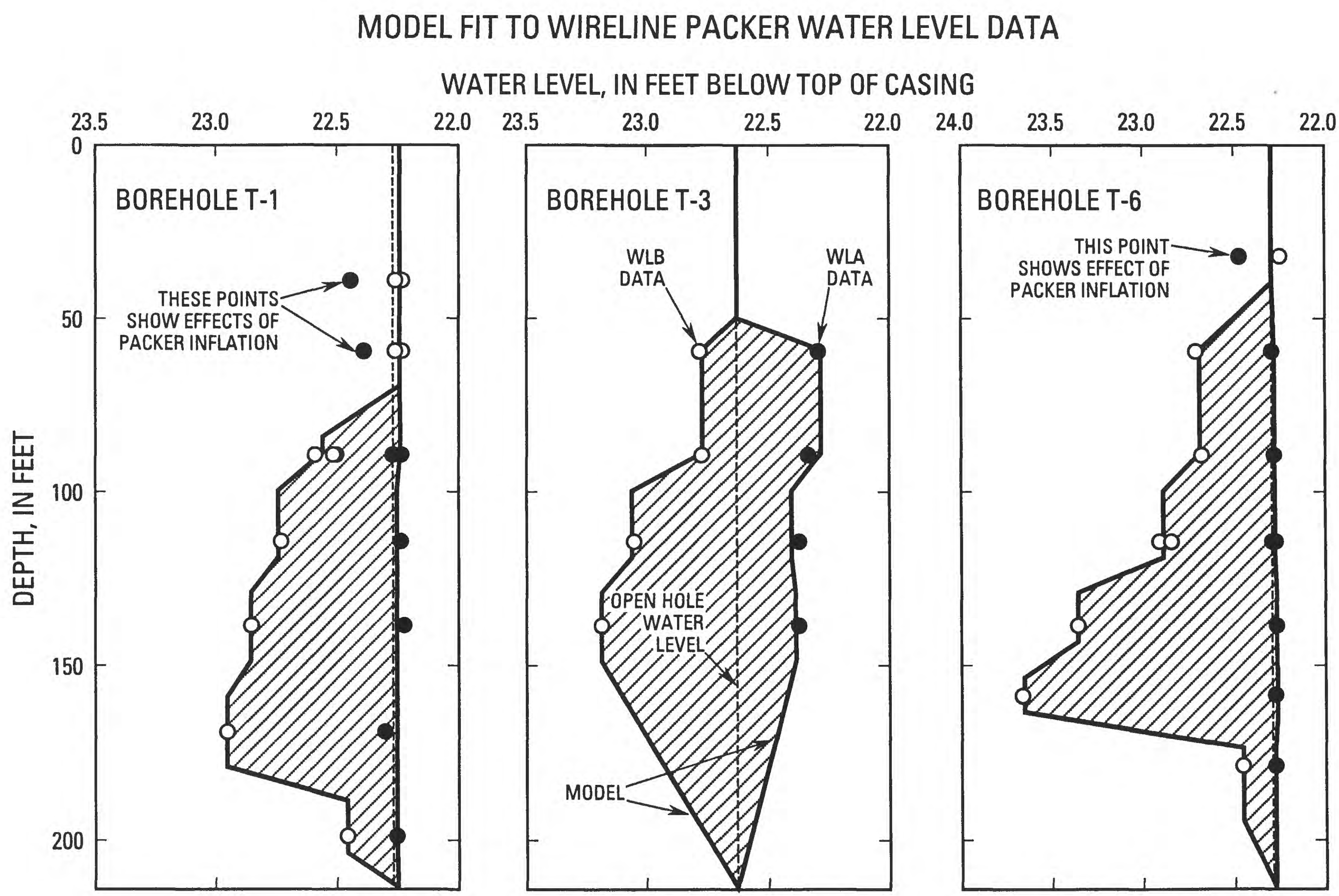

Figure 10. Model-generated and measured water levels for boreholes T-1, T-2, and T-6 at the Belvidere, Illinois, site.

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TABLE 2. Comparison of measured wireline-packer water levels and model predictions

Permeable zone in feet below top of casing	Packer depth in feet below top of casing	Relative head in feet below top of casing	Relative transmis-sivity	Water levels in feet below top of casing			
				Predicted		Measured	
				Above	Below	Above	Below
Borehole T-1							
Open-hole water level				22.25		22.30	
70-90	---	0.20	30.00	---	---	---	---
(Packer)	90	---	---	22.25	22.57	22.25	22.54
90-115	---	0.00	0.80	---	---	---	---
(Packer)	115	---	---	22.26	22.75	22.24	22.74
115-140	---	0.00	0.15	---	---	---	---
(Packer)	140	---	---	22.26	22.86	22.23	22.86
140-170	---	0.00	0.08	---	---	---	---
(Packer)	170	---	---	22.26	22.96	22.31	22.95
170-200	---	-0.75	0.20	---	---	---	---
(Packer)	200	---	---	22.26	22.46	22.26	22.46
200-215	---	0.00	0.10	---	---	---	---
Borehole T-3							
Open-hole water level				22.63		22.67	
50-60	---	0.90	0.70	---	---	---	---
(Packer)	60	---	---	22.29	22.77	22.30	22.78
60-90	---	0.90	0.00	---	---	---	---
(Packer)	90	---	---	22.29	22.77	22.34	22.76
90-115	---	0.70	0.80	---	---	---	---
(Packer)	115	---	---	22.41	23.06	22.38	23.05
115-140	---	0.60	0.20	---	---	---	---
(Packer)	140	---	---	22.40	23.19	22.38	23.19
140-180	---	0.00	0.70	---	---	---	---
Borehole T-6							
Open-hole water level				22.29		22.28	
40-60	---	0.19	30.00	---	---	---	---
(Packer)	60	---	---	22.28	22.68	22.29	22.70
60-90	---	0.00	0.00	---	---	---	---
(Packer)	90	---	---	22.28	22.68	22.29	22.67
90-115	---	0.00	1.50	---	---	---	---
(Packer)	115	---	---	22.28	22.89	22.29	22.88
115-140	---	0.00	0.70	---	---	---	---
(Packer)	140	---	---	22.28	22.36	22.28	22.36
140-160	---	-0.10	0.30	---	---	---	---
(Packer)	160	---	---	22.28	22.67	22.29	22.68
160-180	---	-0.50	0.40	---	---	---	---
(Packer)	180	---	---	22.29	22.47	22.29	22.47
180-215	---	0.00	0.10	---	---	---	---

PARAMETER

	BEST MODEL FIT	MODEL A	MODEL B
h_4	0.9	0.9	0.9
h_3	0.7	0.5	0.7
h_2	0.6	0.3	0.6
h_1	0.0	0.0	0.0
T_4	0.7	0.7	0.7
T_3	0.9	0.9	0.5
T_2	0.2	0.2	0.5
T_1	0.7	0.7	0.7

WIRELINE PACKER DATA

● WLA MEASUREMENTS

○ WLB MEASUREMENTS

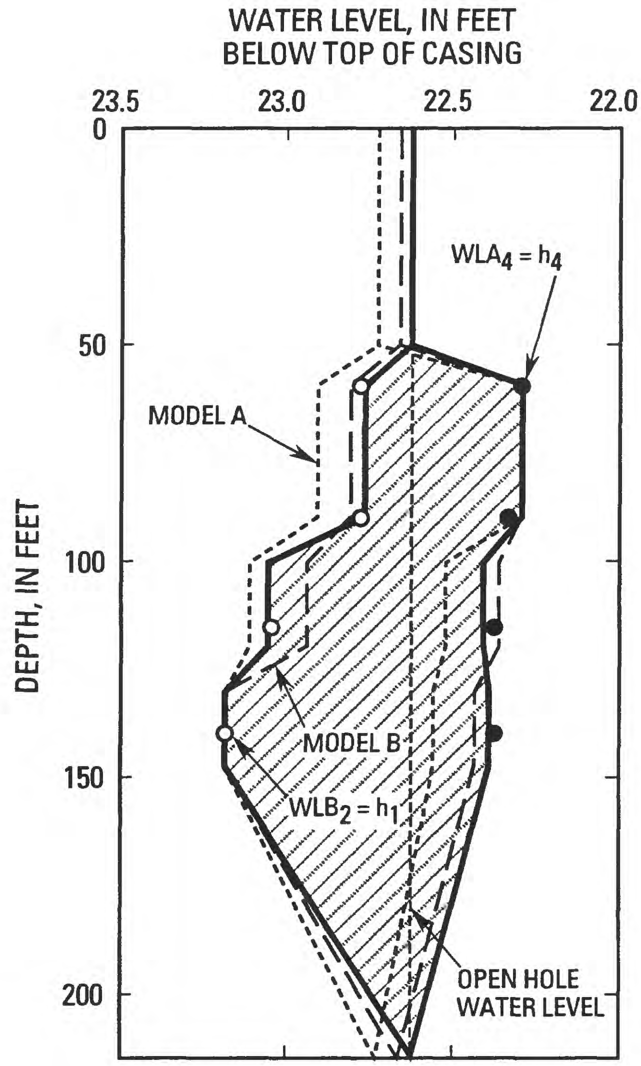

Figure 11. Examples of model predictions of water levels for various sets of values of transmissivity (T_k) and hydraulic head (h_k) compared to the best fit model given for borehole T-3 in figure 8.

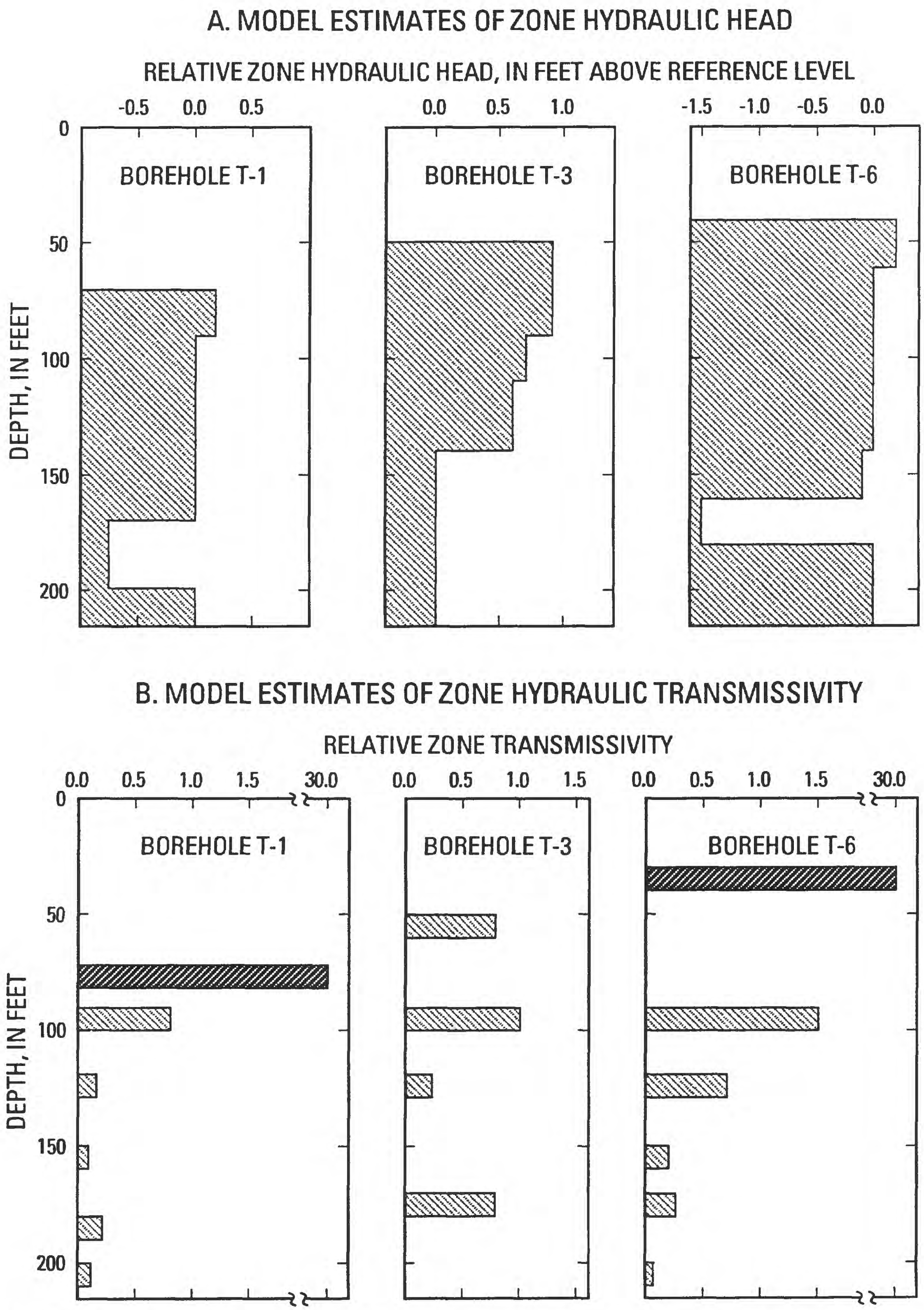

Figure 12. (A) relative zone hydraulic head and B) relative zone transmissivity for the best fit model of water-level data in boreholes T-1, T-3, and T-6 at the Belvidere, Illinois, site. Note the break in scale for T values of the fracture zone in borehole T-1 and the bedding plane in borehole T-6.

factor for any of the nearly horizontal beds. The model computations showed that any transmissivity factor for the two fractures greater than about 30.0 produced an effective fit to the wireline-packer data. The wireline-packer data simply show that any interval of borehole connected to either of these fractures is characterized by a water level that is indistinguishable from the original open-hole water-level model predictions which reproduce this result whenever fracture transmissivity is assigned a relative value of $T \geq 30.0$.

In previous studies, the downward ambient flow in the Belvidere boreholes was attributed to an approximately linear decrease in hydraulic head with depth. Such a condition was expected because the Belvidere boreholes are within the cone of depression of several deep municipal water wells that produced ground water from underlying aquifers. However, the wireline-packer data analysis shows that hydraulic heads are relatively uniform within the formation around the Belvidere boreholes, except for 0.5 to 1.5 ft of drawdown in the 160-190 ft interval. Below the 190 ft zone, the hydraulic head apparently returns to about the same value as found in zones above 160 ft. The highly local nature of the ambient drawdown is clearly indicated for boreholes T-1 and T-6. A similar local drawdown would probably have been measured if additional wireline-packer stations had been used below 160 ft in borehole T-3. The wireline data obtained at the 140 ft station in borehole T-3 probably represents a steep drawdown in the 160-190 ft zone averaged with negligible drawdown in zones above and below the 160-190 ft interval.

The recognition that drawdown is restricted to a very specific depth interval has important consequences in the interpretation of hydrologic conditions at the Belvidere site. The hydraulic heads given in figure 12 indicate that local flow within the Belvidere site is laterally away from the borehole array rather than downward. The drawdown of the underlying municipal wellfield is apparently communicated laterally to the Belvidere borehole array through the 160-190 ft zone and some unknown high-angle connection, rather than directly from below. This result also explains the upward flow measured in the Belvidere boreholes below 190 ft in depth on several previous occasions. These apparent upward flows, which were measured in 1995 and 1996, had been interpreted as possible convective overturning of water in the boreholes rather than a real net upward flow. The wireline-packer data in figures 6-9 demonstrate that an upward hydraulic-head gradient exists below 190 ft in depth, and this vertical gradient probably produced the upward flow.

In previous studies, Paillet (1997), Lane and others (1998), the nearly horizontal sedimentary bedrock penetrated by the Belvidere boreholes was divided into two primary aquifers: an upper aquifer in the 90-100 ft interval and a lower aquifer in the 140-200 ft interval. This interpretation was based on the observed flow under ambient conditions: inflow from fractures above 80 ft, slight increase (figs. 7 and 8) or slight decrease (fig. 8) in flow in the 90-100 ft zone, and outflow in the 140-180 ft zone. The two horizontal aquifers were estimated to have about equal transmissivity and to be at least one full order of magnitude less transmissive than the nearly vertical fracture in borehole T-1 and the bedding-plane fracture in borehole T-6. A similar result is indicated by the wireline-packer data analysis in figure 7, except that the transmissivity of the upper horizontal aquifer (90-115 ft) is slightly larger than the sum of the transmissivity values for the intervals below 140 ft. The wireline-packer analysis also shows that the 140-200 ft aquifer is divided into several beds with barriers to vertical flow, producing the observed confinement of most ambient drawdown to the 160-190 ft zone.

The wireline-packer data analysis also shows a small amount of transmissivity in the 115-140 ft interval in borehole T-1 and T-6, and significant transmissivity in the 50-60 ft interval only in borehole T-3. Therefore, the transmissivity of the 50-60 and 115-140 ft intervals may not be laterally continuous across the borehole array.

CONCLUSIONS

The field tests of the wireline-operated packer demonstrate that the packer can be used to infer the relative hydraulic-head and relative transmissivity values of the zones intersecting a borehole whenever there are measurable hydraulic-head differences between different producing zones. A simple forward model for the prediction of water levels in zones above and below the packer demonstrates that the hydraulic head in each zone represents the transmissivity-weighted average of the hydraulic heads in each permeable zone intersecting the borehole. The model can be used to fit predicted water levels given as a function of producing-zone hydraulic-head and relative transmissivity to the measured water levels at each packer station. Tests of the wireline packer at the Belvidere, Illinois, site show that model interpretations agree with previous results from borehole flow logging and limited straddle-packer hydraulic tests. In addition, the Belvidere tests provide significant insights into site hydraulic conditions that had not been previously obtained using existing hydraulic test techniques.

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