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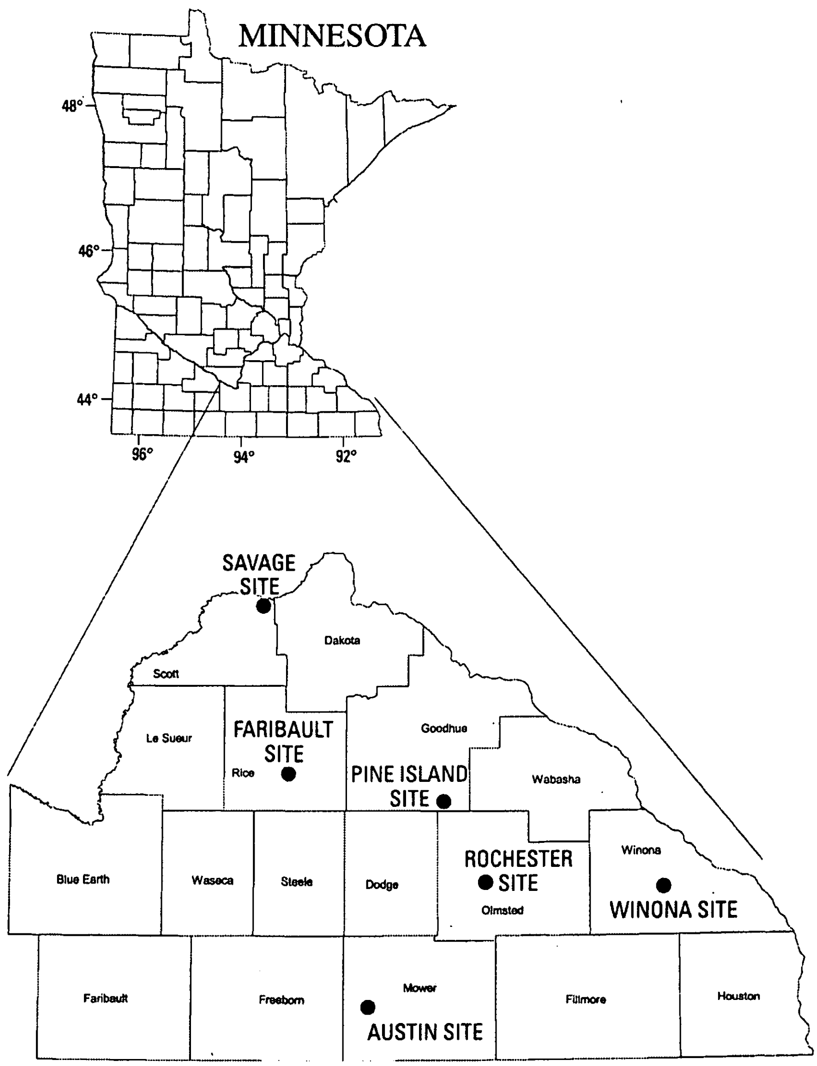

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Cover: Location of six boreholes in southeastern Minnesota.

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By **F.L. Paillet[1], James Lundy[2], Robert Tipping[3], Anthony Runkel[3], Laurel Reeves[4] and Jeffrey Green[4]**

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FIGURES

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second

The following terms and abbreviations also are used in this report:

ohm-meters (ohm-m)
transmissivity (T)
hydraulic head(H)
heat-pulse flowmeter (HPFM)
electromagnetic flowmeter (EMFM)
number of zones (N)
measured ambient flow entering the borehole from zone with index k (Q_k^a)
measured pumping/injection flow entering the borehole from zone with index k (Q_k^b)
difference of Q_k^a and Q_k^b for borehole zone with index k (Q_k^0)
transmissivity of borehole zone with index k (T_k)
gallons per minute (gpm)
borehole televiewer (BHTV)
resistivity (R) [in Table 1]
temperature (T) [in Table 1]

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ABSTRACT

Caliper, gamma, normal resistivity, fluid column temperature and resistivity, and televiewer logs were combined with borehole flow logs to infer the nature of water-producing intervals in six observation boreholes at sites in southeastern Minnesota. Flow profiles were obtained with either the electromagnetic or heat-pulse flowmeters, depending upon equipment availability at the time of logging. Gamma and resistivity logs were used to determine the stratigraphic position of open intervals in each of the boreholes. Water-producing intervals identified using the flowmeter logs were characterized as permeable coarse-clastic beds, solution openings along bedding planes, fractures, or karstic horizons on the basis of gamma, caliper, and televiewer logs. Flow log interpretation theory demonstrates that the hydraulic head and transmissivity of water-producing intervals intersecting an open borehole can be estimated if flow logs are obtained under two different quasi-steady conditions, and if the difference in open-borehole water level between the two conditions can be measured. If logistical conditions prevent flow logging under more than one condition, water-producing zones can be identified, but relative transmissivity values cannot be estimated. If flow logs are obtained under two different flow conditions, but the drawdown between the two conditions cannot be measured, relative transmissivity can be estimated where the zone transmissivity values are given in percent of total borehole transmissivity. Of the six boreholes logged in this study, two different flow logs could be obtained at four sites, and drawdown could be measured at two sites. Thus, quantitative estimates of zone transmissivity and hydraulic head were obtained at the Faribault and Rochester sites, relative permeability profiles were obtained at the Savage and Austin sites, and limited information about water-producing zones were obtained at the Pine Island and Winona sites. Model results indicate that there are seven water-producing zones in the Faribault borehole, with transmissivity values ranging from about 100 to about 1000 ft^2/day, and with hydraulic-head variations of about 2.4 feet within the open borehole interval. The model results indicate four water-producing zones in the Rochester borehole, with transmissivity values ranging from about 10 to almost 500 ft^2/day, and with head variations of about 2.0 feet in the open borehole interval.

INTRODUCTION

A single geologic core or set of well logs serves to define the hydrostratigraphy of homogeneous, stratified aquifers. Aquifers characterized by a heterogeneous distribution of permeability in the form of vugs, fractures, and solution openings are more difficult to describe. Aquifer heterogeneity also introduces scale effects in predicting the performance of production and observation wells constructed at specific locations. A single local sample of aquifer hydraulic properties derived from a flowmeter log may not provide a useful description of aquifer properties in such situations.

Purpose

In this study, a combination of geophysical logs are used to define local aquifer geometry within heterogeneous sedimentary aquifers at six study sites in southeastern Minnesota using a technique described by Paillet (1998) for the characterization of fractured heterogeneous aquifers. The study was designed to identify the water-producing intervals within observation or pilot production wells, and to identify where those zones fit into the regional stratigraphic column. The method is based on quantifying the effects of aquifer drawdown measured in observation wells under the influences of steady pumping from adjacent production wells. It is hoped that this information will result in an improved understanding of aquifer dynamics in the vicinity of production well intakes, and will allow improved monitoring well installation and more effective interpretation of aquifer performance.

Scope

The geophysical well logs described in this report were obtained in six different boreholes at representative locations in southeastern Minnesota (fig. 1). Boreholes were selected as representative of observation or pilot production boreholes completed in various sections of the regional stratigraphic column. The intent was to demonstrate the technique at representative sites where open observation wells and the ability to control well field operations provided suitable conditions for borehole flow logging. The logs were obtained over the period from May 5 to May 10, 1999. A summary of the logs run during this period is listed in table 1. Details concerning the construction, depth, and formations intersected by each borehole are listed in table 2. A list of the water-producing intervals identified in these boreholes is given in table 3.

REGIONAL HYDROGEOLOGY

Regional stratigraphy of southeastern Minnesota is illustrated in figure 2. The sedimentary rocks in this interval are consolidated Paleozoic sandstones, carbonates, and shales ranging in age from Upper Cambrian to Upper Ordovician (Mossler, 1998). These rocks can generally be divided into three classes: coarse clastics, fine clastics, and carbonate rocks (Runkel, 1996, 1998; Setterholm and others, 1991). Core plugs from the coarse clastics suggest poor to moderate cementation, primary porosity from 15 to more than 30 percent, and permeability ranging from 1.0 to as much as 10.0 ft/day (Miller and Delin, 1993). Core plugs from fine clastics indicate variable cementation, total porosity (combined effective and non-effective) from 10 to 30 percent, and horizontal permeability from less than 10^{-4} to 10^{-1} ft/day (Miller and Delin, 1993; Wenck and Associates, 1997). Fine clastics are also characterized by anisotropy caused by bedding, such that horizontal permeability is usually 10 to100 times greater than vertical permeability in these siliclastic rocks (Miller, 1984; Miller and Delin, 1993). Carbonate rocks are generally strongly cemented, have various degrees of anisotropy attributed to bedding, and core plugs have permeabilities similar to those of the fine clastics (Minnesota Geological Survey, unpub. data).

In addition to the primary porosity and permeability of the three classes of consolidated sedimentary rocks, the carbonate rocks contain secondary permeability in the form of fractures, solution openings along bedding planes, and other paleo-karst features (Gianniny and others, 1996; Libra and Hallenberg, 1985). There are numerous fractures and solution openings in the uppermost interval of bedrock. Intervals characterized by shallow bedrock conditions have interval-averaged permeability values one or more orders of magnitude greater than that of unfractured rocks in those intervals (Wenck and Associates, 1997; Gianniny and others, 1996). The lower limit of the shallow bedrock conditions appears to occur at about 100 ft in depth, because borehole image logs and cores indicate open fractures and dissolution features are uncommon below that depth. Information on deep bedrock conditions is relatively limited. On the basis of the limited information available from locations in Minnesota and adjacent states, the secondary permeability of deep bedrock occurs mostly in the form of solution openings along bedding planes and paleo-karst intervals in carbonate rocks below the lower limit of shallow borehole conditions.

METHODS

Geophysical Logs in Consolidated Sedimentary Aquifers

Geophysical well logs are routinely used to characterize the lithology and hydraulic properties of sedimentary rocks (Paillet and Crowder; 1996; Keys, 1990). A suite of gamma and electric logs is often sufficient to determine lithology. Neutron porosity and gamma-gamma density logs in combination with gamma and electric logs can be used to determine primary porosity in coarse clastics, and to separate effective from non-effective porosity in fine clastics, but those logs were not used in this study for logistical reasons. Instead, a combination of acoustic televiewer (a borehole wall imaging device) and flow logs were used to infer the combination of primary and secondary permeability in each interval. The flowmeter logs are used to identify permeable intervals (Paillet and others, 1996). The televiewer log is used to determine the character of the water-producing intervals. When the flowmeter log indicates a discrete "jump" in a flow profile and the televiewer log indicates an associated fracture, bedding plane, or other solution opening, the permeability is assumed to be secondary permeability. When inflow is distributed over a wider interval, and no potential fractures or solution openings are present, the inflow is attributed to primary permeability. In addition, intervals of primary permeability are expected to coincide with intervals of coarse clastics, as indicated by relatively low gamma log counts and relatively high formation resistivity, which are characterized by significant effective primary porosity.

One of the most important considerations in geophysical logging is depth control (Paillet and Crowder, 1996). Quantitative measurements in boreholes consist of two values: the geophysical measurement and the depth measurement. Depth control is a minor issue with most logs, where measurements are made in one continuous run from the bottom to the top of the borehole, and where the logging cable is always under tension. If there is a zero point offset at the completion of the logging run, the discrepancy can be assumed to have occurred during the lowering of the probe, when logging cable tension may have been decreased below the minimum required to turn the measuring wheel used to drive the depth encoding system. In that case, the measured depth offset at the end of logging can simply be added to the entire log.

Depth errors are likely to be more significant in flow logging with the electromagnetic and heat-pulse flowmeters for two reasons: 1) the flowmeter probes are equipped with centralizers and diverters (flexible disks to block flow in the annulus around the probe) that are likely to "catch" on borehole irregularities; and 2) flowmeters are often run in the stationary mode where they are moved up and down between discrete measurement stations. Thus, the flowmeters are especially prone to depth errors when being moved down the borehole, and the stationary mode of measurement involves frequent reversals of probe movement which also can cause depth errors. For these reasons, flow measurements usually have more reliable depth scales when made in the trolling mode. Otherwise, there is a trade-off in accuracy between the spatial resolution of the trolled logs and the flow resolution of the stationary data points. Stationary measurements can be calibrated directly in units of borehole flow, but are prone to depth errors because of the reversal of probe movement, and because inflow zones are only defined to within the spacing of measurements. Trolling measurements are less prone to depth errors, and show the precise depth where flow enters the borehole, but the flow values given while trolling are offset by the trolling speed. In addition, trolling measurements are usually made with a diverter that provides a relatively poor fit to the borehole in order to allow the probe to move smoothly. Stationary measurements can be made at depth locations where borehole conditions are likely to allow effective operation of diverters. In contrast, trolling measurements will include data points where diameter effects influence the operation of diverters or when trolling speed is interrupted by the logging probe temporarily "sticking" on a ledge or other obstruction, causing considerable "noise" to be added to the flow profile.

In general, most effective flow logging results when both trolled and stationary data are available. In situations where other logs limit potential inflow zones to a few specific bedding planes or fractures, the stationary measurements provide the best quantitative measurements of flow, and the spacing of water-producing zones can accommodate depth errors of as much as a few feet. When there are many potential inflow points, trolling measurements provide the best indication of inflow locations, but diameter variations and the borehole conditions, along with the operational problems in maintaining a steady trolling speed can significantly affect the quality of the logs.

Quantitative calibration of flow data is given in units of borehole flow (gallons per minute) by regressing probe output against known flow rates in laboratory flow columns. These calibrated discharge values are the data recorded by either the heat-pulse or electromagnetic flowmeter systems. In the calibration set-up, all flow is forced to pass through the measurement section or "throat" of the logging probe. In the field, there is some bypass of flow around the flexible disk or diverter used to block the annulus between logging probe and the borehole wall. Field measurements are multiplied by a correction factor to compensate for the additional flow bypassing the measurement section. The correction factor is estimated in the field by comparing measured flow with known flow values at one or more control points. Such control points are most often found at the top of an open borehole section or in the lower part of casing, when water is being pumped or injected at a known rate. Changes in borehole diameter such as those indicated by the caliper log, or the effects of borehole irregularities on the efficiency of the diverter, can sometimes introduce significant scatter in the flow measurements.

Borehole Flowmeter Interpretation

High-resolution borehole flowmeters, such as the heat-pulse (HPFM; Hess, 1986; Paillet and Crowder, 1996) and the electromagnetic flowmeter (EMFM; Molz and Young, 1993; Molz and others, 1994), can be used to determine the permeability of intervals intersecting open intervals of boreholes. In the simplest situations, flow profiles indicate intervals where flow enters the borehole under a given hydraulic condition. The main advantage of high-resolution flow logging is that aquifer tests can be run under low-flow conditions. When boreholes are pumped at rates of a few gallons per minute, drawdown stabilizes quickly, and inlet losses in screens and pipe flow losses in the well bore can be neglected. Disposal of produced water at contaminated sites also poses problems, so that flowmeter experiments conducted at low discharges minimize the amount of water for disposal.

The one significant limitation on high-resolution flow logging at low production rates is that the drawdown produced by pumping may be smaller than ambient hydraulic-head differences within the borehole. In such situations, the relative proportion of inflow in a given water-producing interval may be very different from the relative transmissivity of that interval. The relative amount of inflow to the borehole, calculated from the difference in rate of flow above and below and inflow interval, is used to estimate inflow zone transmissivity (Molz et al., 1989). The inflow under quasi-steady conditions is proportional to the product of transmissivity and hydraulic-head difference driving the flow. Since the head differences may be significantly different for each zone, the relative inflows are often not proportional to interval transmissivity. In fact, it is not uncommon to observe downflow between producing zones under ambient conditions. A small amount of pumping may not be enough to reverse this downflow. In such situations, there is outflow in some zones even during pumping. Acceptance of this outflow at face value would indicate negative transmissivity, which is clearly not possible.

The interpretation of vertical flow profiles in open boreholes where there is a vertical hydraulic-head gradient involves the analysis of flow data sets for both transmissivity and hydraulic head in each water-producing zone. Flow into or out of the borehole is assumed to occur through porous beds or fractures that can be modeled as ideal confined aquifers in the immediate vicinity of the borehole. If data are obtained under steady or quasi-steady conditions, aquifer storage coefficient can be ignored, but two such flow profiles are needed to solve for the double set of parameters, transmissivity (T) and zone hydraulic head (H). Considering the number of unknown variables to be determined, there are 2N values of T and H for N water-producing intervals. There will be 2(N-1) values of measured flow in the borehole intervals between the N zones. In addition, there will be two other data points: the drawdown between ambient and pumping conditions, and the pumping rate. Thus, a combination of flow profiles under ambient and steady pumping conditions provide the 2N data points needed to "solve" for the 2N values of T and H. The general numerical formulation of the flow equations used to solve the flow equations for the T and H values are given by Molz et al. (1989) and Paillet (1998).

In the simplest flow logging situation, flow is obtained under only a single hydraulic condition, which is usually ambient flow. Such limited flow logging situations arise when pumping or injection is not possible. There are also situations where hydraulic conditions are changing during the flow measurement period, so that steady flow profiles cannot be made. In these cases, flow logs can be used to identify the "hydraulically active" zones within a borehole. No other interpretation is possible under these circumstances.

In fact, the amplitude of inflow or outflow under even steady ambient conditions can be misleading. The water level in an open borehole represents the transmissivity-weighted average of the water levels in the individual zones connected to the borehole. In other words, the zone with lowest T controls flow between borehole intervals. Thus, the hydraulic conditions in the borehole act to minimize the hydraulic gradient driving flow from the most permeable zones into or out of the borehole. This, in turn, causes the inflow or outflow from the most transmissive zones to appear no different from the inflow or outflow from one or more of the other zones. Thus, relatively low transmissivity zones may have a negligible effect on the borehole water level, but a major or even dominant effect on the measured borehole flow.

A qualitative transmissivity profile can be obtained from a pair of flow profiles if drawdown cannot be measured. This condition applies to two common situations: 1) water level change cannot be measured because there is cascading water when "pumping" is performed by injection; and 2) the formation is so permeable that drawdown is too small to measure. In such situations, there are only 2N-1 data points with which to solve for the 2N hydraulic parameters. The best we can do is to eliminate the effects of H, and then solve for all of the T values as multiples of one. This gives a qualitative transmissivity profile. A quantitative scale may be added at a later time when well tests give an estimate for total well transmissivity - usually performed at a pumping rate high enough that head differences between the producing zones can be neglected. The head values are eliminated from the analysis by subtracting the data from the two flow profiles according to the equation (subtraction of inflows method; Paillet, 1998):

$$Q_k^0 = Q_k^b - Q_k^a$$

$$\frac{T_k}{\sum T_i} = \frac{Q_k^0}{\sum Q_i^0}$$

where Q_k^a and Q_k^b are the measured inflow for the zone k (obtained by subtracting the flow below the fracture from that above the fracture in the profile) obtained under flow conditions "a" (usually ambient) or "b" (pumping or injection). Outflow is expressed as negative inflow. The relative transmissivity for zone k is then expressed as the ratio of the Q_k^0 for zone k with the total of all the Q^0 values. An important part of this analysis is that the signs on the right hand side of the first of these two equations should be consistent, either positive for pumping (where there is net inflow), or negative for injection (where there is net outflow). If the difference for one such zone has the "wrong" sign, this indicates a condition that is hydraulically impossible. Small values with the wrong sign result from measurement errors, indicating that the relative transmissivity of a zone is effectively too small to estimate. A large value with the wrong sign indicates there is a major problem with the data set.

When two steady flow profiles are obtained and the change in water level between these two conditions can be measured, then the full set of T and H values can be estimated by modeling the flow data. This is a simple forward-modeling problem, where the borehole flow is predicted for a given set of values for T and H values until the model predictions lie within an acceptable limit of the measured flow (Paillet, 2000). Iterative methods, where the mean square difference between model and data are used to converge on the model fit, have not proven effective. This result is attributed to the strong non-linearity of the model, where predicted flows are determined by the product of the T and H values. However, flow model analysis confirms that there is a single, unique set of T and H values which allows an acceptable fit of the model to the two steady flow profiles whenever the drawdown between ambient and pumping or injection is known.

RESULTS

The flowmeter profiles and geophysical logs from the six Minnesota sites provided various levels of information about hydraulic conditions at each location. Fully successful characterization was achieved at two of the six sites, where site conditions and equipment logistics allowed unambiguous formulation of a flow log interpretation. The results obtained at each of the sites, and the degree of interpretation possible with the given geophysical log data are presented in the following subsections of this report. In representing the flowmeter data for the boreholes at each site, the figures plotting that data use a consistent notation throughout. Stationary flow measurements are given as solid dots for ambient flow data, and as open dots for flow data obtained under pumping or injection conditions. Trolled flowmeter profiles are given as light continuous lines. Interpretation of both stationary and trolled flow data are given as heavy solid lines superimposed on the flow plots. The interpretation lines are vertical over those intervals where flow is assumed to be constant. The interpretation lines shift either to the left or right over those intervals where inflow or outflow is assumed to occur. The size of the shift and the depth interval over which that shift occurs are clearly shown in each figure. In those situations where a model is fit to either data or interpretations of the data, the predictions of the flow model are superimposed as heavy dashed lines on the flow data plots. Original televiewer log images cannot be readily displayed with the flow log data because of the great difference in scale between the two classes of data. Televiewer log results are summarized in the geophysical and flowmeter data composite figures using the conventions presented in figure 3.

Savage Site

Although the Savage borehole is open to the 520-680 ft interval, all of the inflow to this borehole is confined to the 580-660 ft interval (fig. 4). Flow was measured with the EMFM with a flexible diverter to funnel flow into the measurement throat. The EMFM output gives flow in gpm through the measurement throat. A field calibration was obtained by measuring the downflow in the casing during the 9 gpm injection. This calibration showed that the nominal flows given by the EMFM had to be multiplied by a factor of 6.0 to give true flow for measurements in the Savage borehole. This multiplication factor is similar to values obtained under similar conditions at other sites. A short interval of steady upflow was detected under ambient conditions. Thus, an aquitard is present at about 595 ft, separating the aquifer into upper and lower zones (table 3). Most of the outflow under injection occurs in the lowermost zone. When the subtraction of inflows method is used to compensate for the effects of hydraulic-head difference between the zones, the lower zone accounts for 82 percent of the water production from this well. The other 18 percent appears to originate from a thin zone a few feet above. Both zones appear to be permeable beds, since they are not associated with fractures, bedding planes, or solution openings on the borehole televiewer (BHTV) log. The aquitard may be associated with a series of faint shale beds or partings indicated on the BHTV log.

The logs and cuttings recovered during drilling indicate that the Savage borehole is open to the lower part of the Franconia Formation, all of the Ironton and Galesville Sandstones, and the upper part of the Eau Claire Formation (fig. 2). The flowmeter log indicates that most of the inflow to the borehole is derived from the distributed primary permeability of the coarse clastic rocks in the Galesville and Ironton Sandstones. The water-producing zone correlates with an interval of low gamma activity (590-640 ft) that probably indicates a clean sandstone. Both trolling and stationary flow measurements were made with the EMFM. The trolled data confirm that inflow in this interval is not concentrated near bedding plane openings, but is evenly distributed over the entire interval.

The flow logs also indicate a small inflow coming from a thin interval just above 590 ft in depth. This zone is hydraulically isolated from the water-producing zone below because there is a small amount of ambient flow between zones. This water-producing zone is apparently in the lower part of a fine clastic interval in the lower part of the Franconia Formation extending from 570 to 590 ft. Because there is no obvious bedding plane or fracture indicated on the BHTV log, this inflow may be associated with either thin beds of medium to coarse-grained sand within the fine clastic rocks, or bedding plane openings that do not show up very well on the BHTV image log.

Faribault Site

The BHTV log for the Faribault borehole shows numerous bedding planes and karst horizons, as well as a few near-vertical fractures (fig. 5). These fractures strike about N60E, but do not seem to be associated with inflow to or outflow from the borehole. Flow logging was begun by taking stationary flow measurements with the EMFM. The flowmeter was used without diverter, because there was a relatively small annulus between probe and borehole wall, and because initial attempts to use the EMFM with diverter showed that the diverter interfered with movement of the probe in the rough borehole. Probe response was calibrated in casing while pumping at 2.0 gpm. Nominal flow measurements had to be multiplied by a factor of about 15.0 in a 4-in diameter borehole to give total borehole flow. Stationary EMFM measurements give accurate flow values, but are not very efficient at defining the exact depths of inflow or outflow in aquifers where other logs show many possible inflow depths. The EMFM data show there was a complex downflow profile in the Faribault borehole, which was only slightly suppressed during pumping at 2.0 gpm (fig. 5). Thus, the only place where the measured flow during pumping was upwards was above the bottom of casing. Everywhere else, the pumping only served to slow the ambient downflow rather than turn it around into upflow.

Although the stationary flow values give accurate measurements at a single point, they do not very effectively indicate exactly where flow enters the borehole between measurement stations. This was a problem in the Faribault borehole, because there were so many possible entry points. The repeated movement of the probe up and down to identify inflow points also increased the likelihood that depth errors would build up over time. Seven possible flow zones were inferred from the limited flow data. One clear diagnostic that there are problems with the interpretation in figure 5 is given by the subtraction of inflow method to infer relative flow zone transmissivity (table 3). The subtractions produce negative numbers, indicating that one or both flow profiles inferred from the flow data points in figure 5 may be in error.

Possible depth errors in the flow profile inferred from the data in figure 5 can be addressed by comparing these results with flow logs obtained while trolling the EMFM at a constant speed. The trolled logs (fig. 6) have significant diameter effects and the trolling speed (which may vary slightly) is superimposed on the borehole flow. Some of the noise in the data may have been caused by the probe catching on bedding planes during the logging. The moving probe measures the difference of water movement due to borehole flow and the movement of the probe itself, and not just borehole flow. But the trolled logs do clearly show the precise depths where flow shifts in response to exit or entry. The two sets of flow data (stationary and trolled; fig. 7) are combined to identify the exact inflow points, and to assign numerical flow values to "plateaus" on the trolled logs. There are several intervals near the bottom of the well where there are just not enough stationary values to adequately fix the flow "steps" in figure 7. This is now identified as the source of our problem in analyzing the data in figure 5. The combined data sets give a set of zone values that now make sense (table 4). The one zone where there is a small negative value of -0.1 can be attributed to measurement scatter where the difference is too small to measure, and can be effectively assigned a relative transmissivity value of 0.0. A numerical model fit (Paillet, 1998) to the flow data (fig. 8) is used to estimate the T and H values for the water-producing zones indicated in figure 6. A detailed discussion of the analysis of the flow data from the Faribault borehole is given in Appendix 1.

Based on this information, three of the water-producing zones in the Faribault borehole are karstic horizons at about 115, 172, and 182 ft in depth. All of the these zones are located in the Shakopee Formation of the Prairie du Chien Group. Although some minor intervals of primary porosity are known to occur in this interval, essentially all of the water-production from the Faribault borehole is associated with bedding planes or other karstic features. The most permeable zone is a series of bedding planes right at the bottom of casing. These may be closely connected to the overburden. The zone at about 208 ft may be a weaker karstic zone. The zone near 80 ft is apparently a bedding plane, but the response here is complex, because the televiewer and gamma together show there is a shale here, too. So the zone may be a bedding plane just above or below a shale bed. The major water-producing zone at the very bottom of the borehole may be below televiewer coverage, and appears to be a paleo-karst horizon developed along the regional unconformity at the contact between the Shakopee Formation and the underlying Oneota Dolomite.

The flow profiles given in figure 6 for the two steady flow profiles in the Faribault borehole were modeled using the numerical technique of Paillet (1998), and an acceptable fit to the profiles and the measured drawdown of 0.1 ft was found with the flow model predictions within the ±0.5 l/min of the measured flow (fig. 8). The details of this analysis and the resolution of the inconsistencies in the subtraction of inflow results (table 3) based on stationary flow data for this site (fig. 5) are discussed in Appendix 1. The revised zone flows and subtraction of inflow estimates of relative zone T based on the flow data in figure 7 are listed in table 4. The estimates for the T and H values for the seven water-producing zones in the Faribault borehole are listed in table 5A. The results indicate that the uppermost three zones have the same hydraulic head, and probably represent a single aquifer sub-unit. The hydraulic head is lowest in the 170-190 ft interval, and increases again between 190 ft and the bottom of the borehole. Although three of the zones appear to have about the same transmissivity (800-1000 ft^2/day), the 172 ft zone appears to be drawn down by pumping from the Faribault wellfield more than the other zones on the basis of the aquifer hydraulic heads given by the model fit. The sum of all of the transmissivity values of the seven zones (about 4000 ft^2/day) can be used to estimated the productivity of a production well screened over the open-borehole interval (48-230 ft) in the Faribault wellfield.

Pine Island Site

No meaningful flowmeter logs were obtained at this site for logistical reasons related to scheduling use of a production well immediately adjacent to the Pine Island borehole (fig. 9). The other gamma logs show that the open borehole is divided into two sand (coarse clastic) intervals separated by a 20-ft-thick fine clastic bed (380-405 ft), where the gamma response is related to the presence of fine-grained, feldspathic sand with relatively little shale. All of these units are within the Jordan sandstone (fig. 2). The BHTV log shows a prominent bedding plane at the top of the fine clastic bed near 380 ft in depth, and a single steeply dipping fracture striking about N60E in the 360-370 ft depth interval. When the adjacent city supply well was turned on, the water level in this observation well dropped almost immediately from above 15 ft below land surface down to almost 100 ft below land surface. During limited EMFM measurements, oscillating flow was observed in the casing which was interpreted as the harmonic oscillation of the water column in response to the sudden lowering of water level when the adjacent production well was put into operation.

Rochester Site

The Rochester borehole is open to the Shakopee Formation under shallow bedrock conditions, characterized by a relatively high density of fractures and dissolution features. This borehole contained weak ambient upflow measured with the HPFM at the time of logging (fig. 10). The EMFM could not be used because of equipment failure. The BHTV log shows there are two sets of fractures: a set of N60E striking near-vertical fractures (for example, near 125 ft in depth), and shallow dipping (20-40 degrees) fractures striking roughly north-south (for example, the fractures in the 90-105 ft depth interval). HPFM flow log data show inflow at the time of logging was associated with shallow dipping fractures and/or bedding planes near the bottom of casing (90-95 ft), and in the 122-130 ft and 165-170 ft intervals. Another inflow zone appears to be associated with karst-like features on the televiewer log near 205 ft in depth. However, the subtraction of inflows method (table 2) shows that the upper two zones are much more permeable than the lower two zones, which together account for less than five percent of the ground water production from this borehole.

The flow profiles given in figure 10 for the two steady flow profiles in the Rochester borehole were modeled, and an acceptable fit to the profiles and the measured drawdown of 0.48 ft was found (fig. 11). The zone flows and subtraction of inflow estimates of relative zone T based on the flow data in figure 10 are listed in table 2. The estimates for the T and H values for the seven water-producing zones in the Rochester borehole are listed in table 5B. The results indicate that the two uppermost zones are much more permeable than the two lower zones. There is a small head difference driving flow up from the 130 ft zone. The small ambient upflow from the 167 and 205-210 ft zones is hardly affected by the pumping because that upflow is driven by a head difference that is larger than the drawdown produced by the pumping. The sum of all of the transmissivity values of the seven zones (about 250 ft^2/day) can be used to estimate the productivity of a production well screened over the open-borehole interval (90-210 ft) at the Rochester site.

Austin Site

The Austin borehole is exposed to the Spillville Formation under shallow bedrock conditions as described in the regional hydrogeology section of this report, with a high density of interconnected fractures and karstic features, and with negligible primary permeability. The BHTV log for this borehole shows that there is a major karst zone between 85 and 90 ft. Although this highly permeable zone probably originated as dissolution along one or more bedding planes, the dissolution has removed so much rock in the vicinity of the borehole that no definite interpretation can be made from the BHTV log. There is downflow from this zone into more karst and possible fractures only a few feet below this zone (fig. 12). Pumping at 2 gpm had hardly any effect at all on the downflow, and no measurable difference between water levels under ambient and pumping conditions could be detected. Thus, flow log analysis was limited to the estimation of relative zone transmissivity using the subtraction of inflow method (table 3). The analysis shows that more than 90 percent of the open borehole production is associated with the large solution opening near 86 ft in depth.

Winona Site

The suite of logs run in the Winona borehole was limited to caliper, natural gamma, normal resistivity logs, and the HPFM run under ambient conditions only because of the great depth to static water level and the large diameter of this borehole (fig. 13). The borehole is open to a long interval including the Oneota Dolomite, Jordan Sandstone, St. Lawrence Formation, Franconia Formation, and the Ironton and Galesville Sandstones (fig. 2). The BHTV log could not be obtained because of the large diameter of the open borehole. Weak downflow was present in the well. The flow might have been present over the whole column, but at the time of logging was only large enough to detect over the 300 - 440 ft interval.

Measurable inflow is associated with coarse clastics in the lower part of the Jordan Sandstone, and with the entire thickness of the St. Lawrence Formation. There are some intervals of coarse clastic rocks in the St. Lawrence Formation, but inflow is also probably associated with bedding plane openings in fine clastic rocks. The maximum downflow in the 350-380 ft interval separates the overlying zone of inflow from the underlying zone of outflow. Therefore, the gamma high at 380 ft may be an aquitard. This gamma peak corresponds with a fine clastic zone at the base of the St. Lawrence Formation. Most of the outflow on the HPFM profile occurs in the 380-440 ft interval, corresponding to the coarsest and most permeable part of the Franconia Formation. The downflow indicated by the HPFM data has decreased below detectable levels at 440 ft in depth, where the gamma log indicates a sharp transition to fine clastics.

CONCLUSIONS

Geophysical logs were combined with flow profiles obtained using either the electromagnetic or heat-pulse flowmeters under ambient and pumped conditions (where possible) to identify the depth and character of water-producing zones in six observation boreholes in southeastern Minnesota. Flow logs were analyzed to identify the specific zones contributing inflow or outflow to boreholes under ambient hydraulic-head conditions. The character of each producing zone was determined by comparing water-producing intervals with borehole images obtained with the televiewer to identify possible fractures, bedding planes, and solution openings serving as the source of inflow, and by correlating permeable coarse clastic intervals in the regional stratigraphic column with gamma and electric log signatures indicative of such lithology in the log composites. Ambient flow log data also indicate the presence of regional aquitards because ambient flow would not exist in the absence of such barriers to vertical flow within the formation surrounding the borehole.

At four of the six Minnesota sites, the flow log data could be used to generate a qualitative permeability profile. This analysis is important, because drawdown produced by pumping may be of the same order of magnitude as the naturally-occurring hydraulic-head differences within different aquifer zones. If such hydraulic-head differences occur, they can strongly bias relative permeability estimates based on the percent of production from each zone. The subtraction of inflow method effectively removes that bias, but cannot give a precise, quantitative estimate of zone hydraulic head or transmissivity. In two of the boreholes (Faribault and Rochester sites), reliable flow profiles were obtained under both ambient and pumping conditions, and an accurate measurement of the difference in open borehole water levels between these two conditions could be made. For those two sites, the flow profiles could be uniquely fit to a steady-flow model. Model results indicate that there are seven different water-producing zones in the Faribault borehole, with transmissivity values ranging from about 100 to slightly more than 1000 ft^2/day. The model also gives hydraulic-head estimates, showing there is a maximum head difference of about 2.4 ft within the open borehole section. Hydraulic head is lowest in the central part of the open borehole, and increases both above and below that central interval. For the Rochester site, the flow model fit to the data indicates four water-producing zones, with the two upper zones being much more permeable than the two lower zones. Transmissivity values range from about 10 to almost 500 ft^2/day. Ambient upflow is driven by a head difference increasing from 0.5 to 2.0 feet with depth.

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Table 1. Summary of geophysical logs run in southeastern Minnesota.

SITE	PROBE	LOGS AND COMMENTS
SAVAGE	Caliper	Borehole diameter
	Multi-function	Gamma, Normal R, Fluid T, R
	Induction	Gamma, Induction R
	BHTV	Borehole wall image
	EMFM, stationary	Ambient flow
	EMFM, stationary	Inject at 9 gpm
	EMFM, 10 fpm troll up	Inject at 9 gpm
	Multi-function	Fluid R, T during injection
FARIBAULT	Caliper	Borehole diameter
	Multi-function	Gamma, Normal R, Fluid T, R
	Induction	Gamma, Induction R
	BHTV	Borehole wall image
	EMFM, stationary	Ambient flow
	EMFM, 10 fpm troll up	Ambient flow
	EMFM, stationary	Pump at 2 gpm
	EMFM, 10 fpm troll up	Pump at 2 gpm
	Multi-function	Fluid R, T during pumping
	EMFM, stationary	Right after turn-on city well
	EMFM, stationary	Hour after turn-on city well
	EMFM, 10 fpm troll up	Hour after turn-on city well
PINE ISLAND	Caliper	Borehole diameter
	Multi-function	Gamma, Normal R, Fluid T,R
	Induction	Gamma, Induction R
	BHTV	Borehole wall image
ROCHESTER	Caliper	Borehole diameter
	Multi-function	Gamma, Normal R, Fluid T,R
	Induction	Gamma, Induction R
	BHTV	Borehole wall image
	HPFM, stationary	Ambient flow
	HPFM, stationary	Pump at 2 gpm
AUSTIN	Caliper	Borehole diameter
	Multi-function	Gamma, Normal R, Fluid T, R
	Induction	Gamma, Induction R
	BHTV	Borehole wall image
	HPFM, stationary	Ambient flow
	HPFM, stationary	Pump at 2 gpm
	EMFM, 10 fpm troll up	Ambient flow
	EMFM, 10 fpm troll up	Pump at 2 gpm

Table 1. Summary of geophysical logs run in southeastern Minnesota--Continued

SITE	PROBE	LOGS AND COMMENTS
WINONA	Caliper Multi-function HPFM, stationary	Borehole diameter Gamma, Normal R, Fluid T, R Ambient flow

Notes:
BHTV = Borehole televiewer
EMFM = Electromagnetic flowmeter
HPFM = Heat-pulse flowmeter
R = Resistivity in ohm-meters
T = Temperature, in degrees F

Table 2. Summary of boreholes logged in southeastern Minnesota.

SITE	DATE LOGGED	NOMINAL DIAMETER (inches)	TOTAL DEPTH (feet)[1]	DEPTH CASING (feet)[1]	DEPTH WATER LEVEL (feet)[2]	OPEN FORMATIONS
SAVAGE	5/5/99	4	680	517	NM[4]	Franconia Ironton/Galesville Eau Claire
FARIBAULT	5/6/99	4	225	47	14.5	Shakopee Oneota
PINE ISLAND	5/7/99	4	452	344	14.3	Jordan
ROCHESTER	5/8/99	6	205	82	16.7	Shakopee
AUSTIN	5/9/99	4	110	77	12.4	Spillville
WINONA[3]	5/10/99	8	600	70	232.0	Jordan St. Lawrence Franconia Ironton/Galesville

Notes:
1. All depths given below reference point at top of casing.
2. Static water level at the start of logging.
3. Open formations include only formation below water level in Winona borehole.
4. NM indicates water level not measured at time of logging.

Table 3. Summary of relative transmissivity profiles expressed as percent of total borehole transmissivity for the four boreholes where paired ambient and pumped or injection flow profiles were obtained.

DEPTH INTERVAL (ft)	ZONE TYPE	CONDITION A (gpm)	CONDITION B (gpm)	DIFFERENCE (gpm)	PERCENT
		Savage site - Observation well #593579			
		Ambient	Injection		
582-586	a or b	-1.2	-2.8	1.6	18
605-640	a	1.2	-6.2	7.4	82
TOTAL		0.0	-9.0	9.0	100
		Faribault site - Observation well #625327			
		Pumping	Ambient		
48	b	5.8	5.0	0.8	40
80	c	1.0	0.9	0.1	5
115	e	2.0	2.1	-0.1	-5
172	e	-4.5	-5.4	0.9	45
182	e	-1.8	0.0	-1.8	-90
208	b	-0.5	-2.6	2.1	105
224	e	0.0	0.0	0.0	0
TOTAL		2.0	0.0	2.0	100
		Rochester site - Observation well #485610			
		Pumping	Ambient		
87-92	b	0.55	-0.80	1.35	68
129-131	b and d	0.85	0.30	0.55	28
167	b	0.40	0.35	0.05	2
205-210	e	0.20	0.15	0.05	2
TOTAL		2.00	0.00	2.00	100
		Austin site - Observation well #613746			
		Pumping	Ambient		
82-87	f	4.20	2.35	1.85	93
92-100	c or e	-2.20	-2.35	0.15	7
TOTAL		2.00	0.00	2.00	100

ZONE DEFINITIONS

- a Permeable bed without fractures or bedding planes
- b Bedding plane or set of planes with possible minor solution enlargements
- c Bedding plane or set of planes with significant enlargement by solutioning
- d Fracture or set of fractures, possibly enlarged by solutioning
- e Paleokarst horizon characterized by irregular solution openings
- f Cavernous zone possibly developed on bedding planes or paleokarst horizon

Table 4. Relative transmissivity of water-producing zones in the Faribault borehole expressed as percent of total borehole transmissivity computed by the subtraction of inflows method and based on trolled electromagnetic flowmeter data in figure 7.

ZONE NO.	DEPTH (ft)	FLOW[1] (gpm)		INFLOW[2] (gpm)		DIFFERENCE	PERCENT OF TOTAL T
		AMBIENT	PUMPED	AMBIENT	PUMPED		
-	---	0.00	1.80	----	----	----	
7	48	----	----	5.50	6.30	0.80	44.0
-	---	-5.50	-4.50	----	----	----	
6	80	----	----	1.10	1.30	0.20	11.0
-	---	-6.60	-5.80	----	----	----	
5	115	----	----	1.40	1.20	-0.20	-11.0
-	---	-8.00	-7.00	----	----	----	
4	172	----	----	-4.60	-4.20	0.40	22.0
-	---	-3.40	-2.80	----	----	----	
3	182	----	----	-2.30	-2.30	0.00	0.0
-	---	-1.10	-0.50	----	----	----	
2	200	----	----	-0.50	-0.50	0.00	0.0
-	---	-0.60	0.00	----	----	----	
1	224	----	----	-0.60	0.00	0.60	33.0
-	---	0.00	0.00	----	----	----	
TOTAL	---	----	----	0.00	1.80	1.80	100.0

NOTES:

1. Positive flow is upflow and negative flow is downflow.
2. Negative inflow denotes outflow.

Table 5A. Estimated transmissivity and hydraulic-head values for the seven water-producing zones in the Faribault borehole based on flow model matching.

ZONE	DEPTH (ft)	Hydraulic head (ft)	Water level (ft below TC)	Transmissivity (ft^2/day)
7	48	2.4	11.2	1023.00
6	80	2.4	11.2	140.00
5	115	2.4	11.2	140.00
4	172	0.0	13.6	837.00
3	182	0.0	13.6	279.00
2	208	0.8	12.8	93.00
1	224	1.1	12.5	837.00

COMPUTED STATIC WATER LEVEL	1.225 ft
COMPUTED PUMPED WATER LEVEL	1.107 ft
DIFFERENCE (DRAWDOWN)	0.118 ft
MEASURED DRAWDOWN	0.12 ft

Table 5B. Estimated transmissivity and hydraulic-head values for the seven water-producing zones in the Rochester borehole based on flow model matching.

ZONE	DEPTH (ft)	Hydraulic head (ft)	Water level (ft below TC)	Transmissivity (ft^2/day)
4	87-92	0.0	16.4	440.00
3	129-131	0.5	15.9	165.00
2	167	2.0	14.4	28.00
1	205-210	2.0	14.4	11.00

COMPUTED STATIC WATER LEVEL	0.299 ft
COMPUTED PUMPED WATER LEVEL	-0.187 ft
DIFFERENCE (DRAWDOWN)	0.486 ft
MEASURED DRAWDOWN	0.48 ft

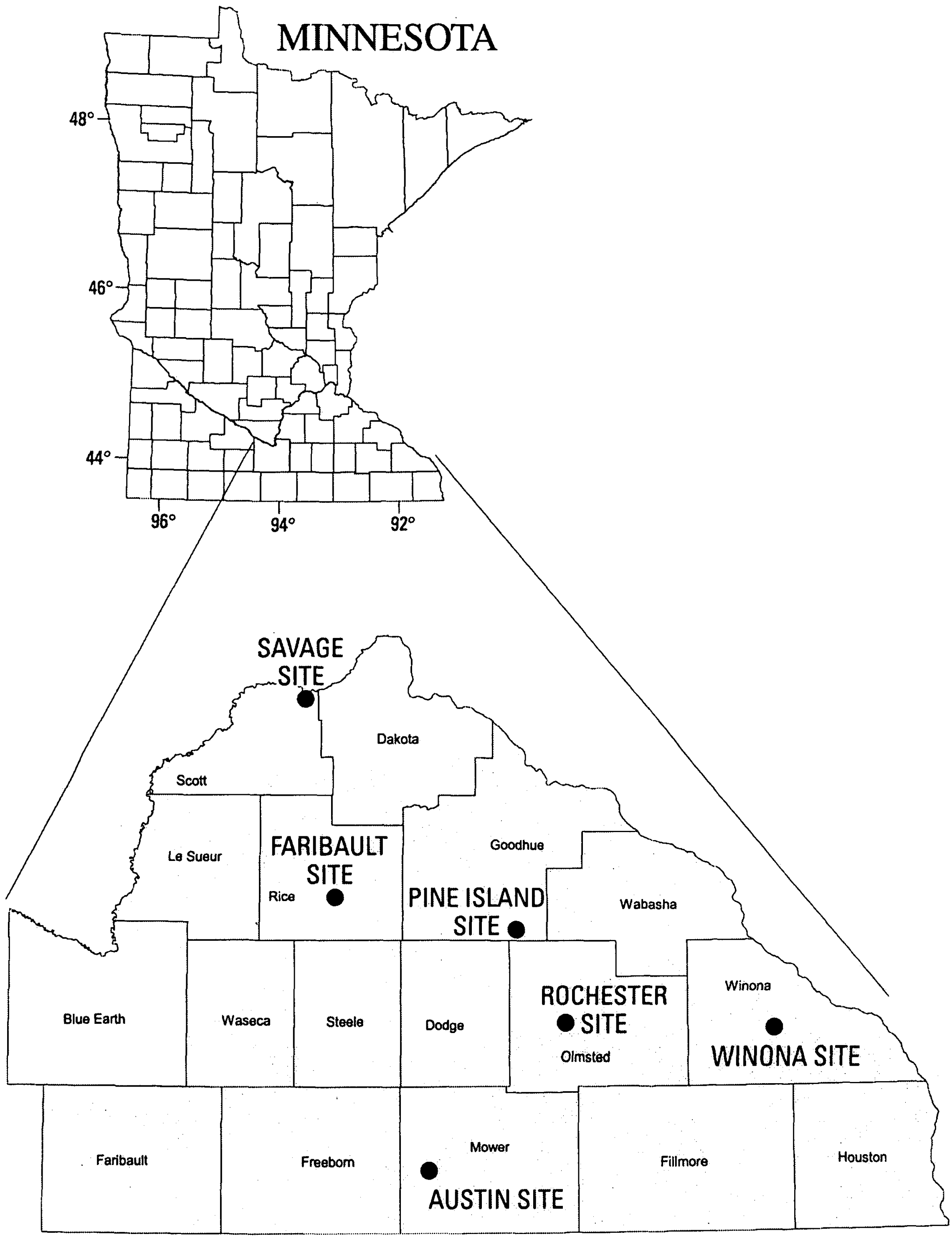
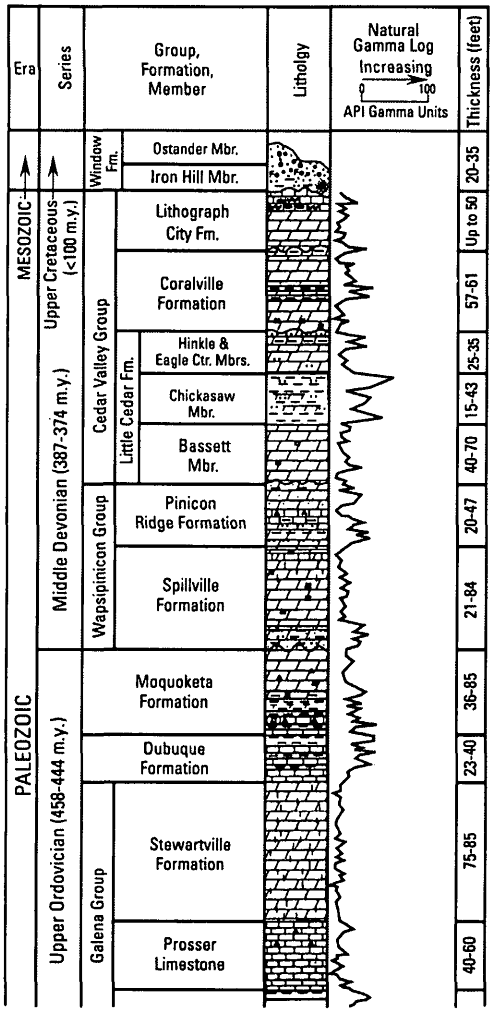


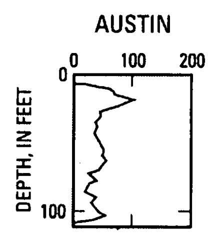
Figure 1. Location of the six boreholes in southeastern Minnesota.

(A)

STRATIGRAPHIC COLUMN



GAMMA LOGS FROM MINNESOTA SITES, IN COUNTS PER SECOND



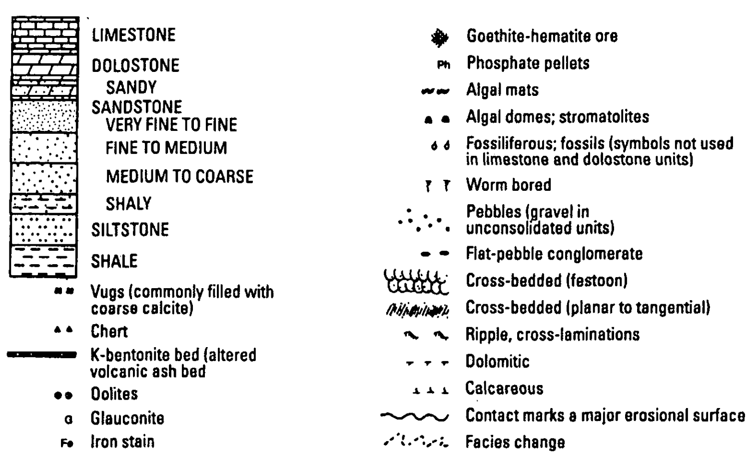


Figure 2. Regional stratigraphic column divided into A) upper and B) lower sections, showing the gamma logs from the six study boreholes for comparison with the typical gamma signatures given by Mossler (1998).

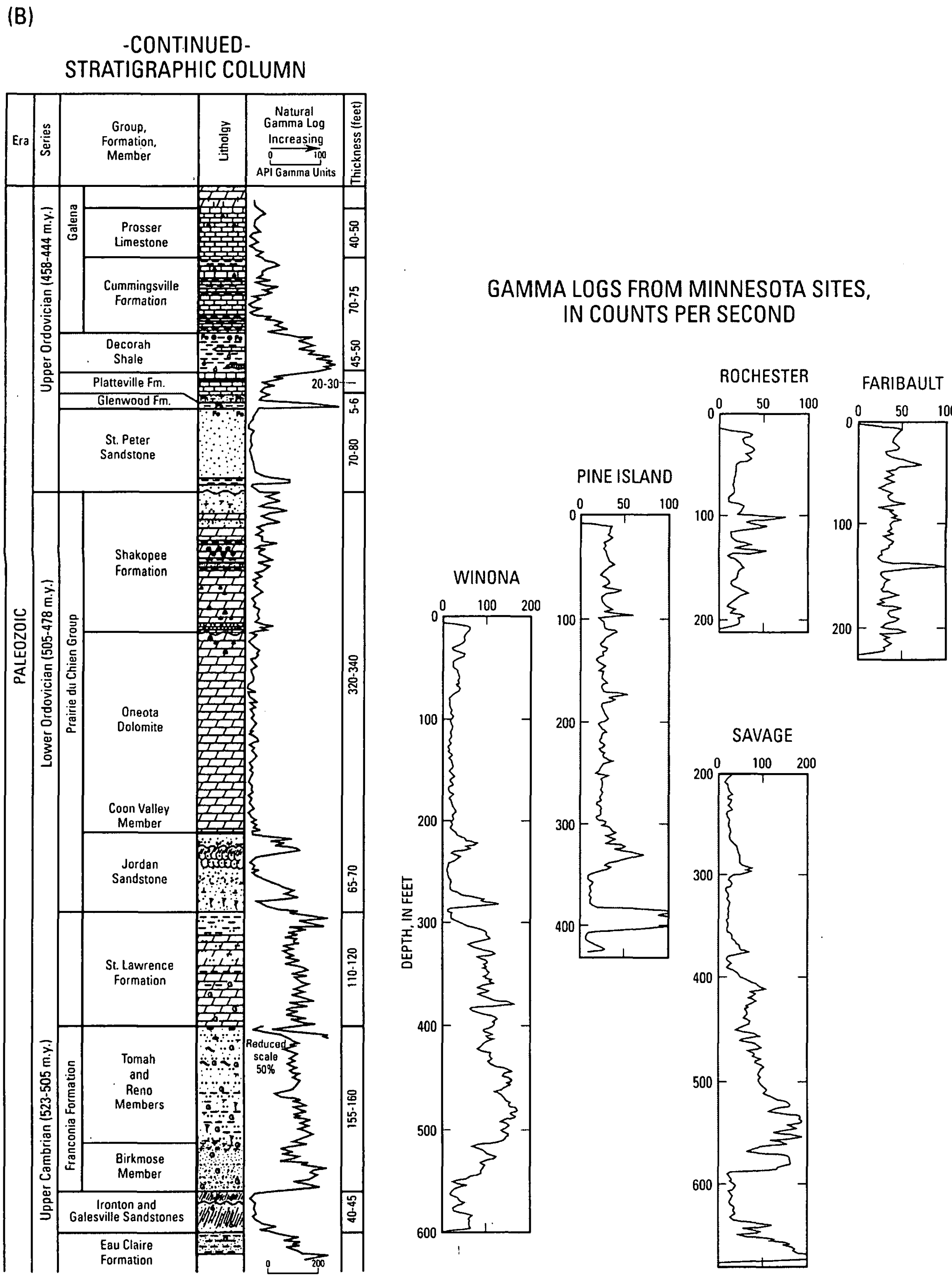


Figure 2. Regional stratigraphic column divided into A) upper and B) lower sections, showing the gamma logs from the six study boreholes for comparison with the typical gamma signatures given by Mossler (1998)--Continued

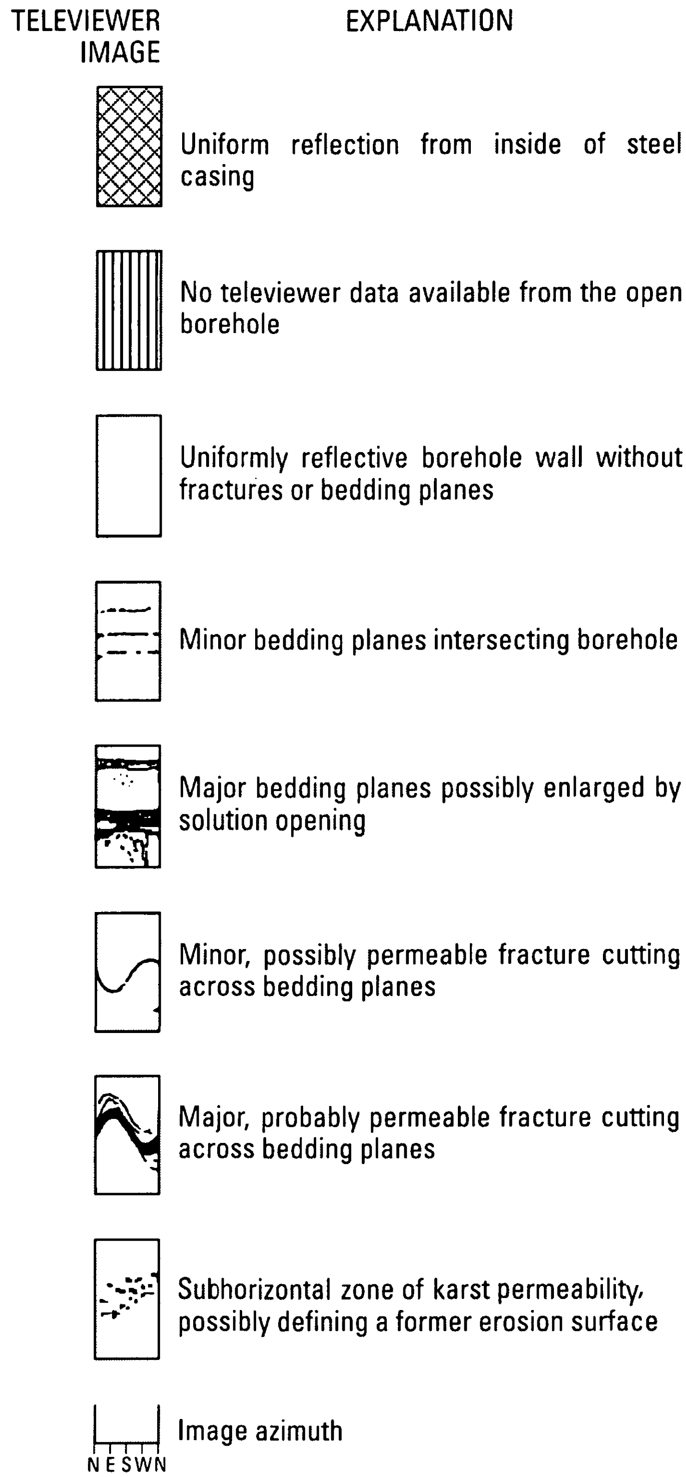


Figure 3. Explanation of graphical representation of televiewer logs used in figures 4-7 and figures 9-13.

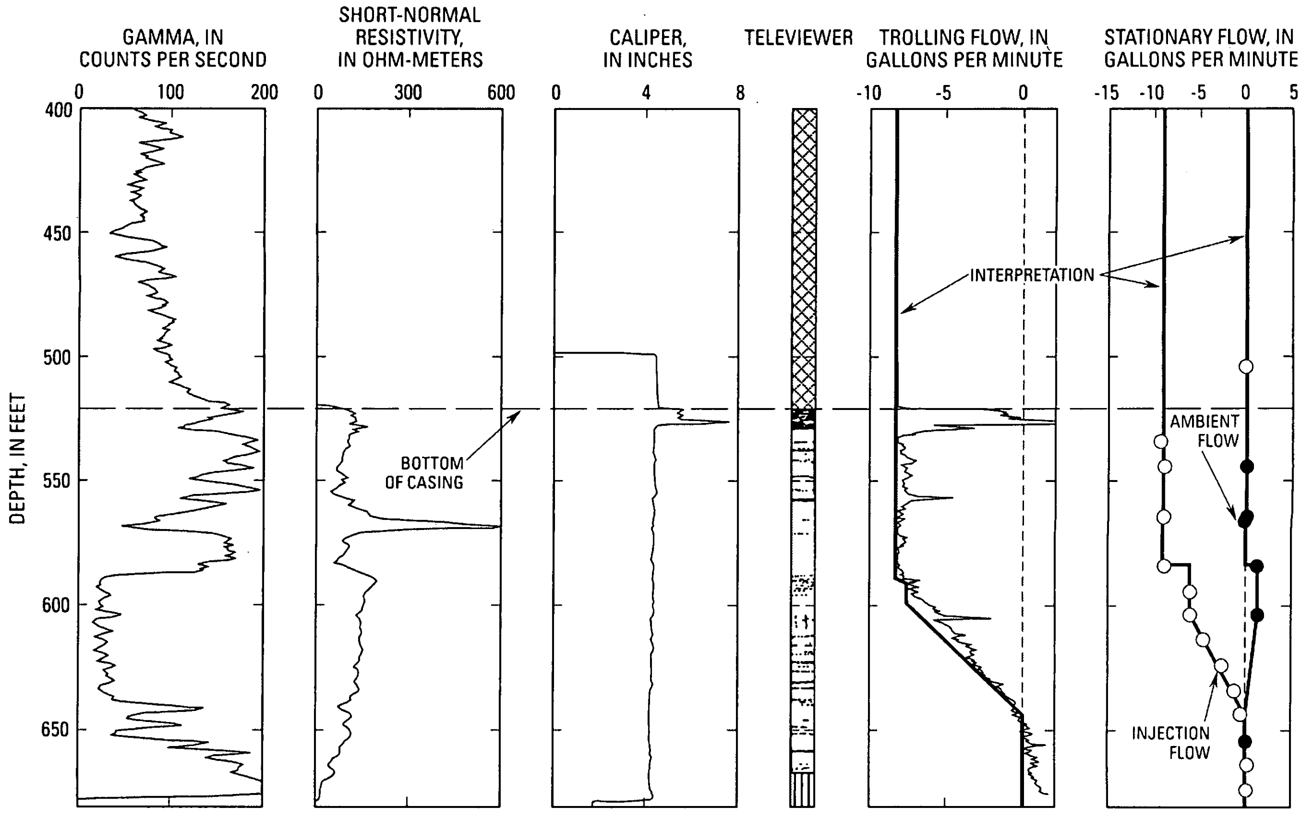


Figure 4. Electromagnetic flowmeter profiles obtained under ambient (stationary) and injection (stationary and trolling) conditions compared to other geophysical logs for the Savage borehole.

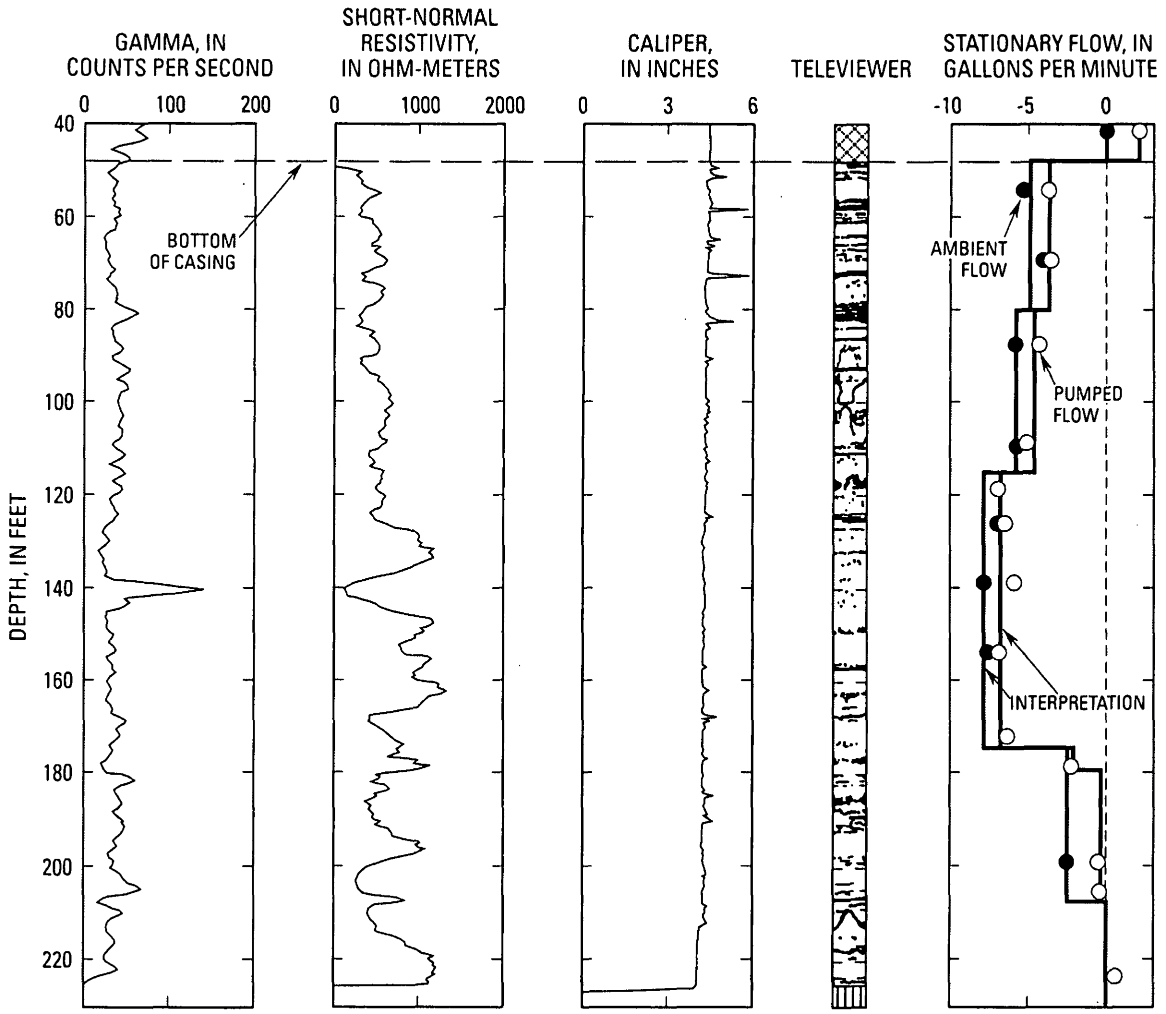


Figure 5. Stationary electromagnetic flowmeter data obtained under ambient and pumping conditions compared to other geophysical logs for the Faribault borehole.

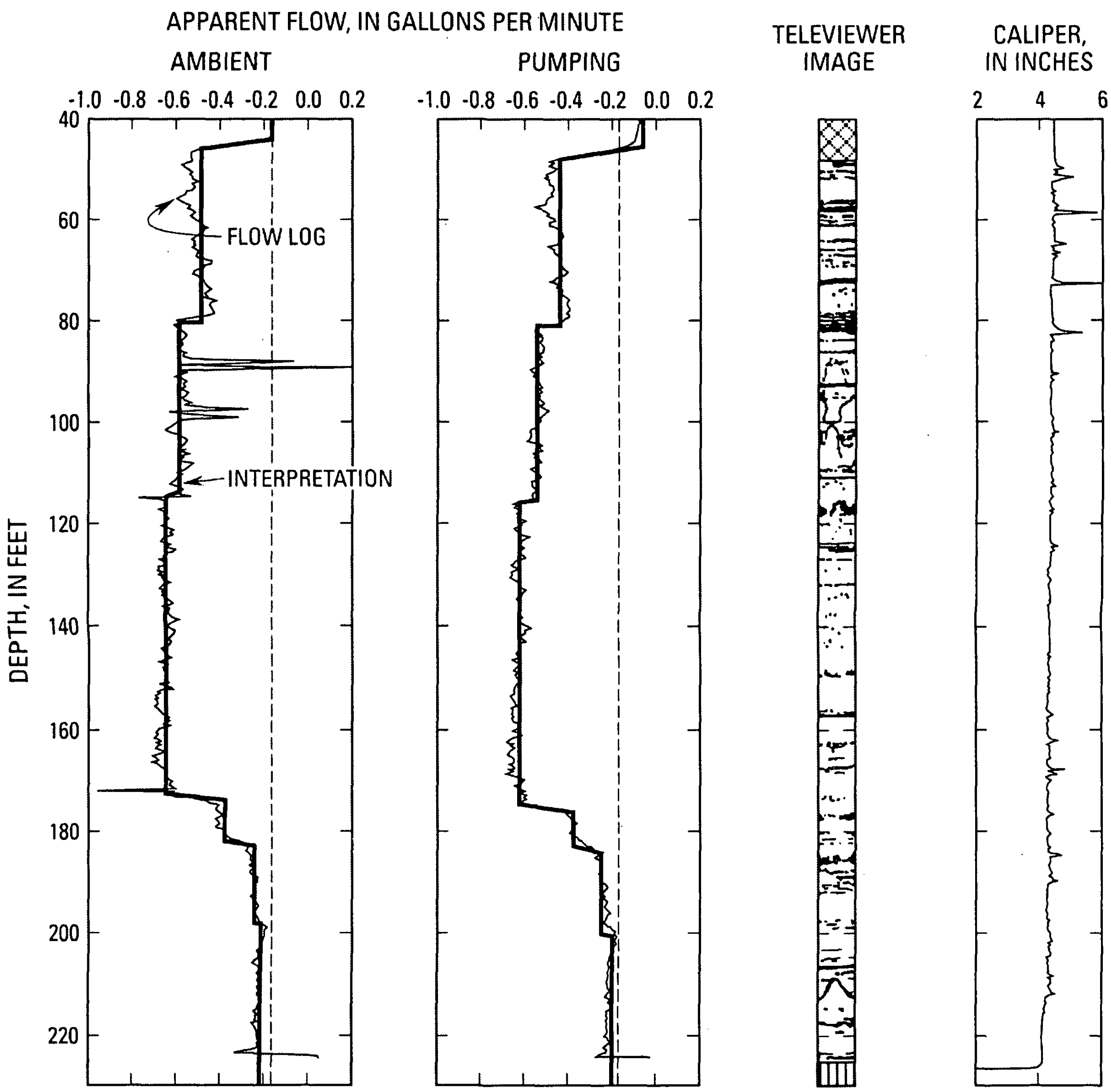


Figure 6. Electromagnetic flowmeter profiles obtained in the Faribault borehole while trolling upward at about 10 ft per minute under ambient and steady pumping conditions; the flow scale represents the flow through the probe measurement section while trolling and not true borehole discharge, and the dashed line represents the response equivalent to no net borehole flow.

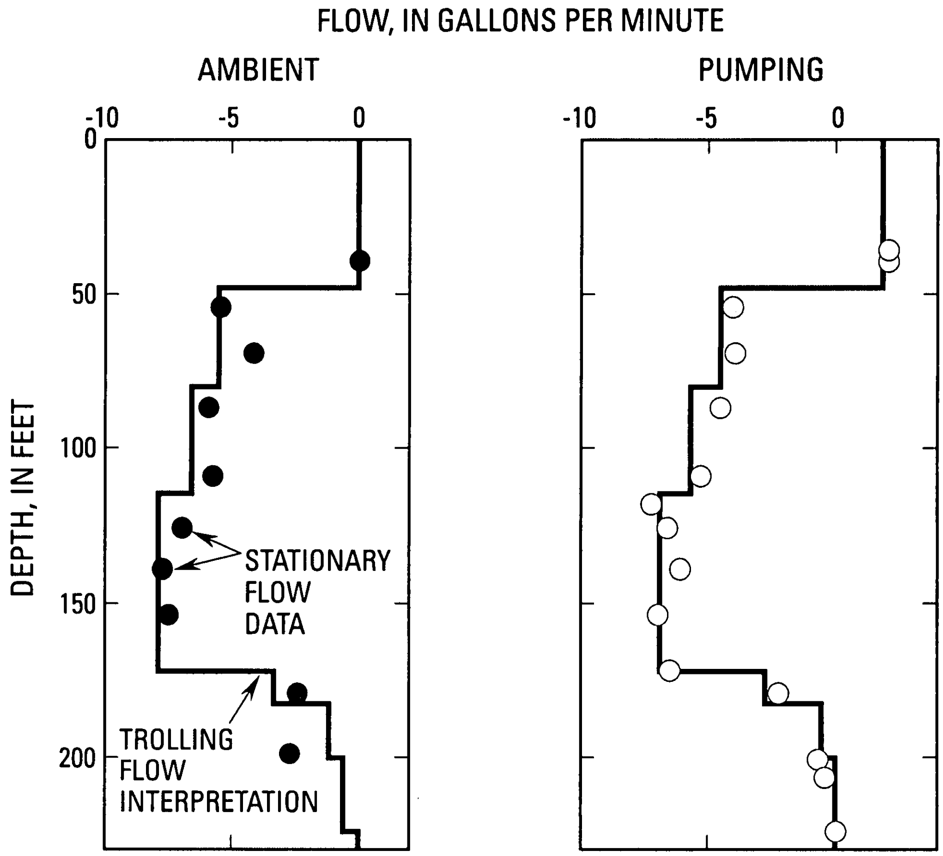


Figure 7. Trolled electromagnetic flowmeter profile interpretation for the Faribault borehole calibrated to produce a true borehole discharge scale by shifting the profiles to fit the stationary flow data.

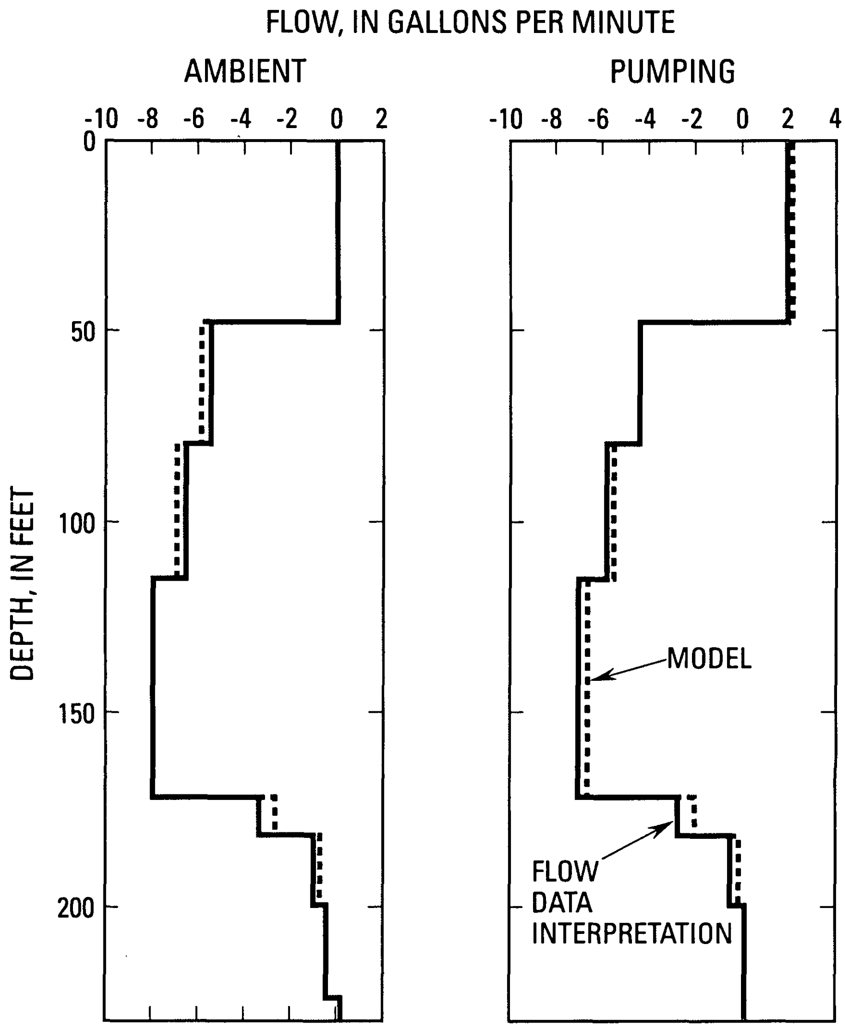


Figure 8. Borehole flow model computations fit to trolled electromagnetic flowmeter profiles for the Faribault borehole; model parameters are listed in table 4.

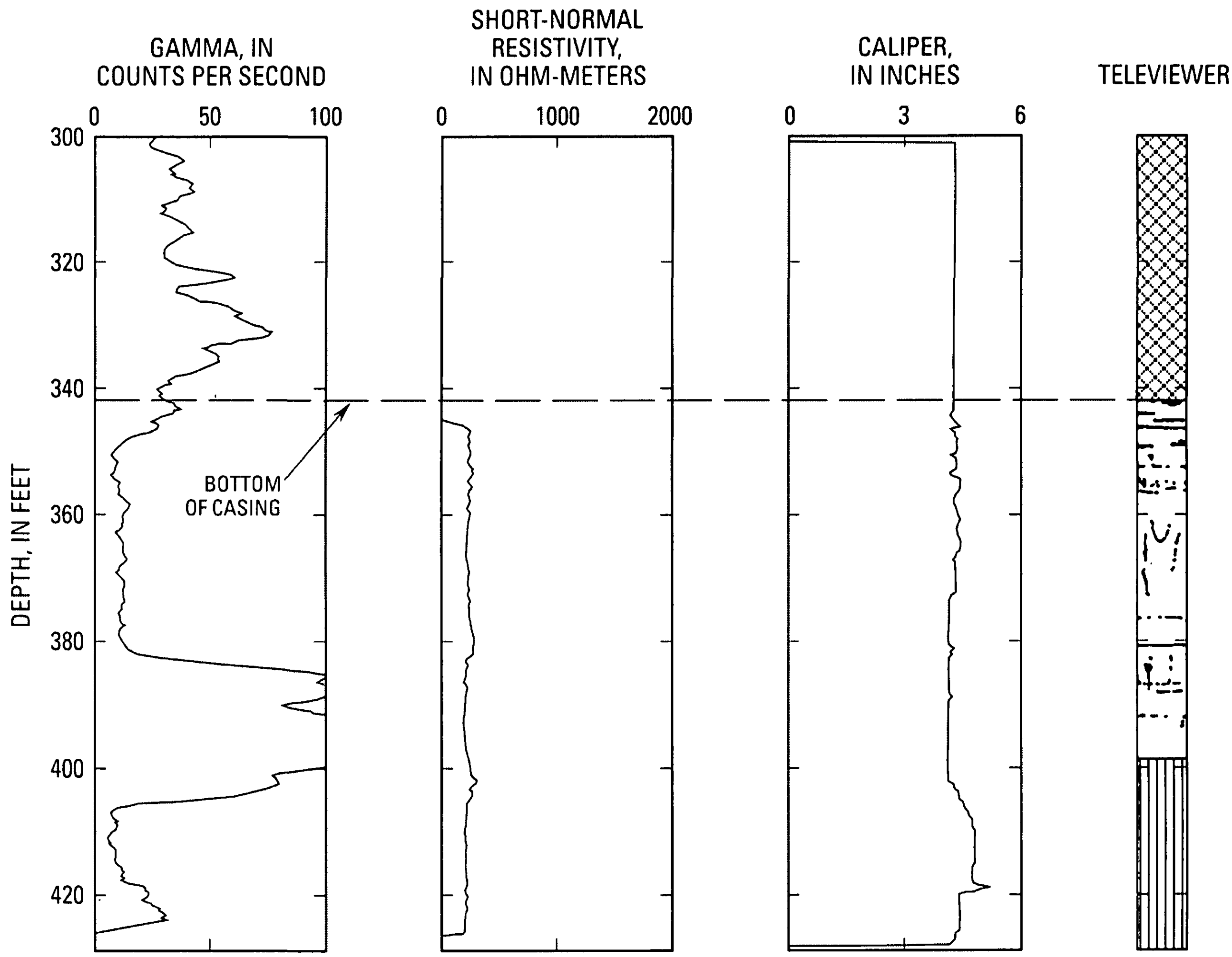


Figure 9. Geophysical logs for the Pine Island borehole.

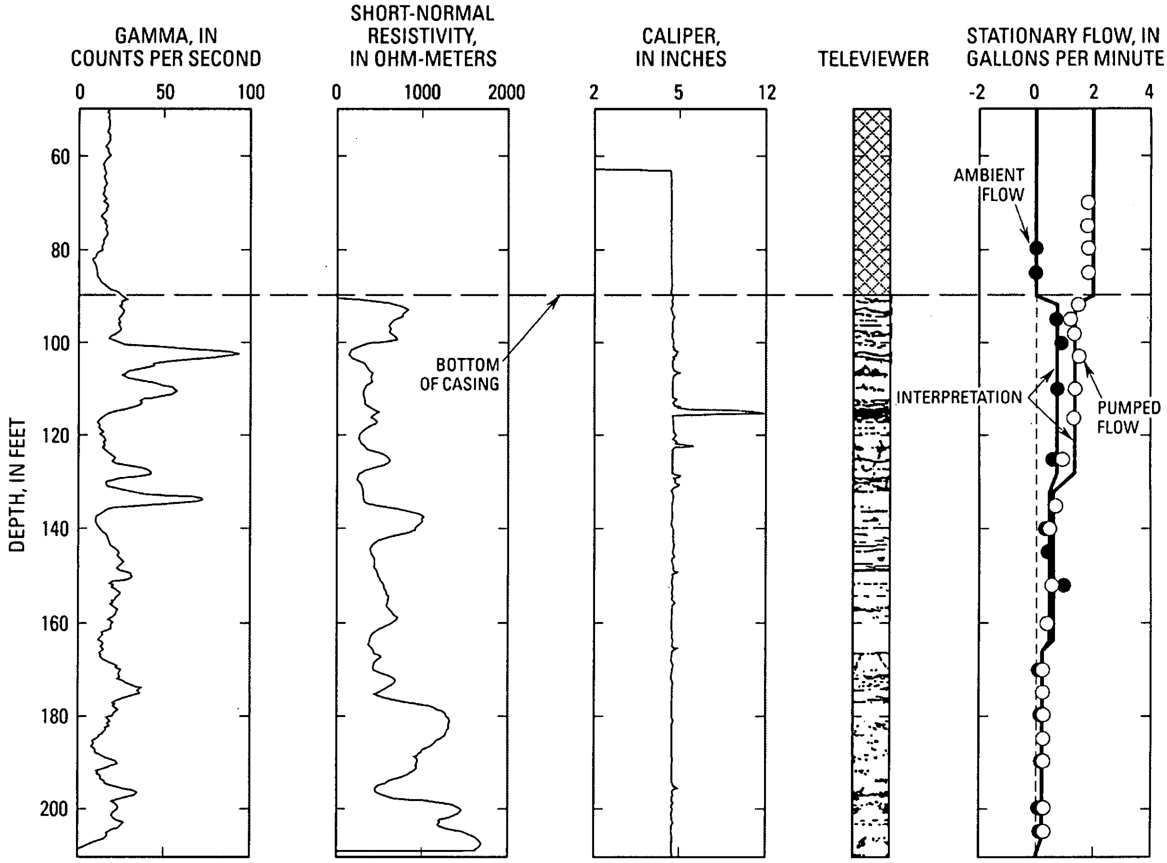


Figure 10. Stationary heat-pulse flowmeter data obtained under ambient and pumping conditions compared to other geophysical logs for the Rochester borehole.

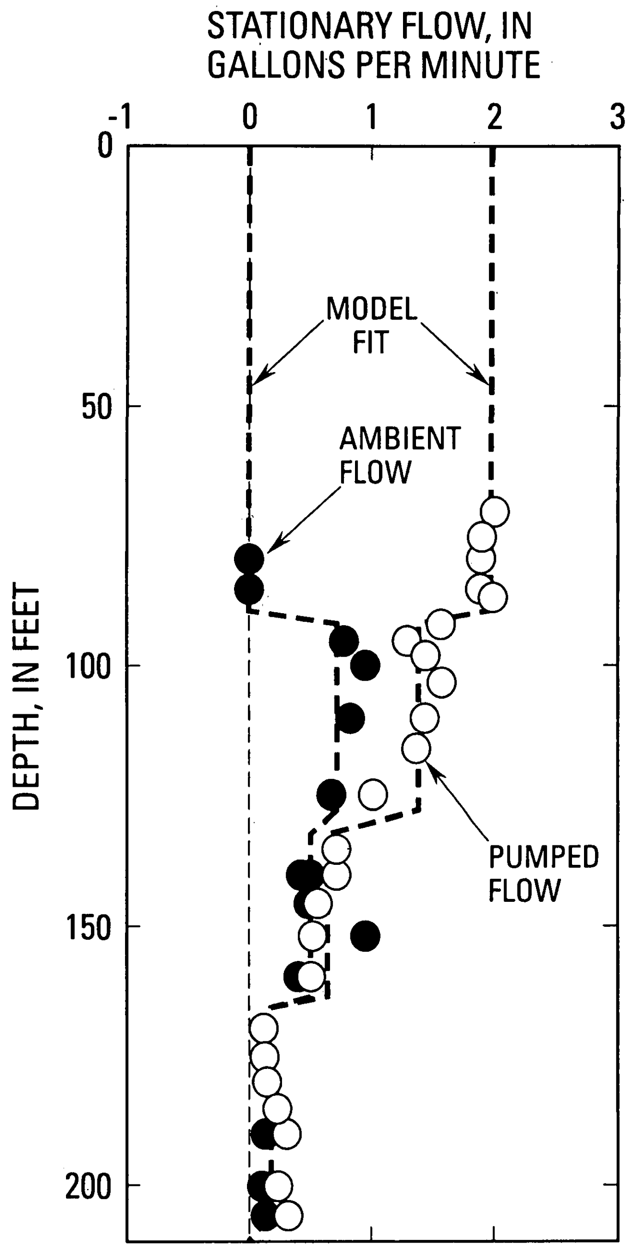


Figure 11. Borehole flow model computations fit to the stationary heat-pulse flowmeter data for the Rochester site.

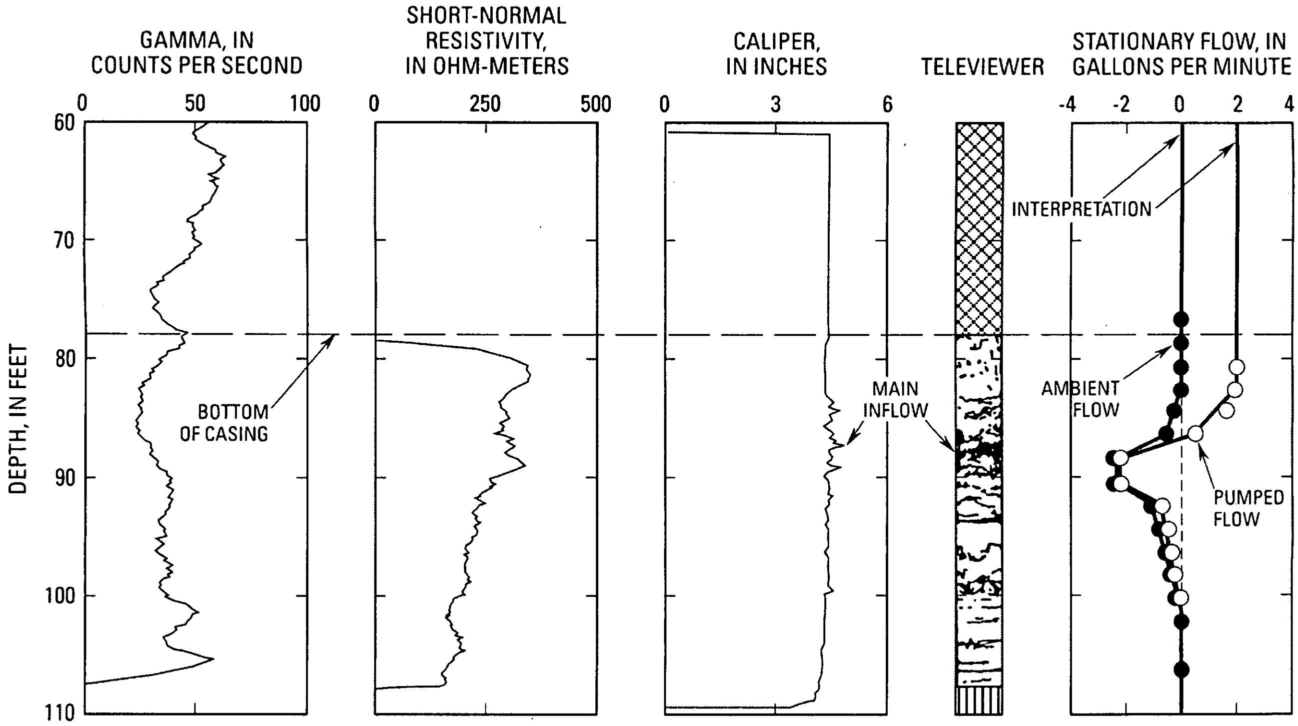


Figure 12. Stationary heat-pulse flowmeter profiles obtained under ambient and pumping conditions compared to other geophysical logs for the Austin borehole.

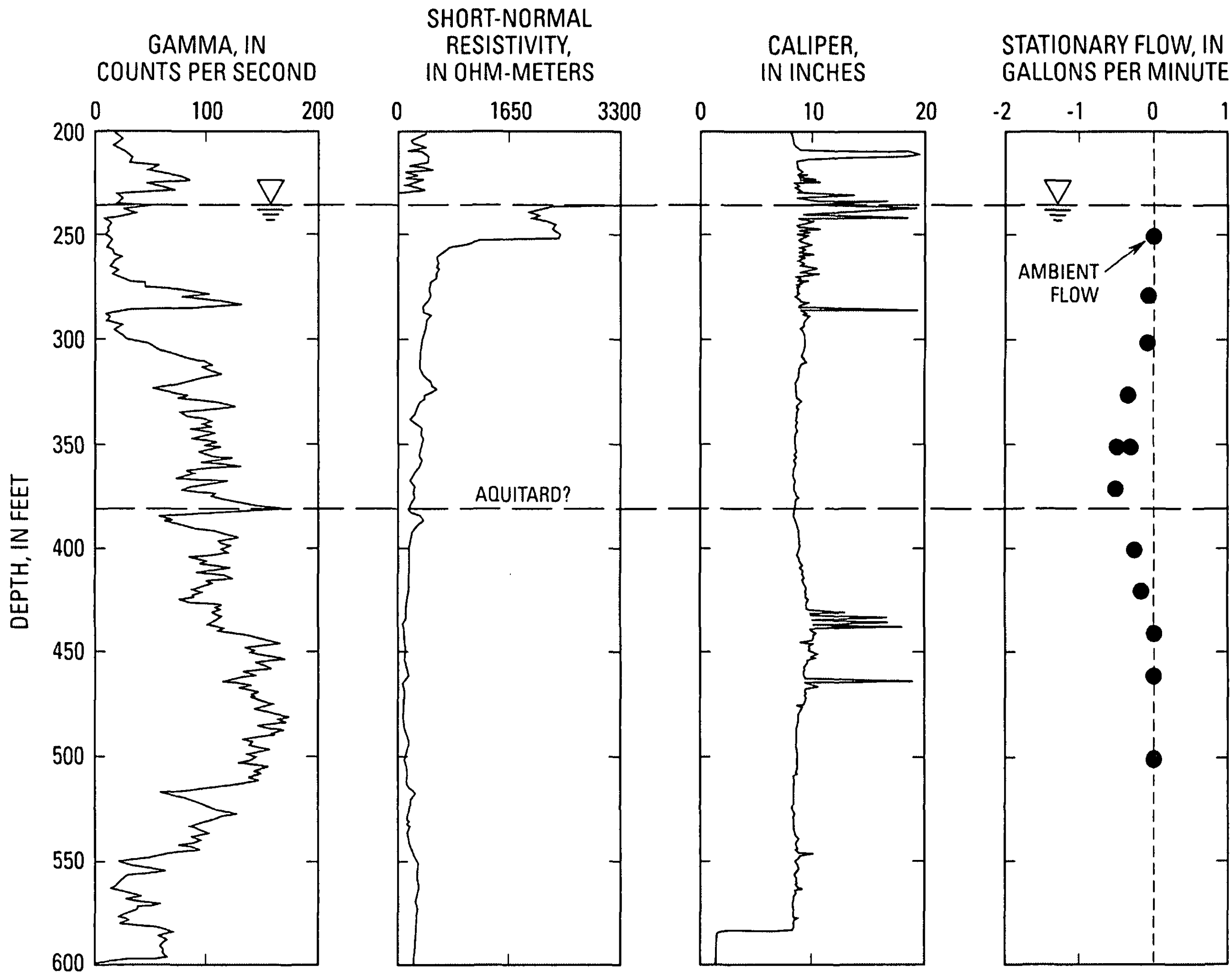


Figure 13. Stationary heat-pulse flowmeter data obtained under ambient conditions compared to other geophysical logs for the Winona borehole.

APPENDIX 1. **Faribault flow log interpretation**

The theory of flow log interpretation demonstrates that a unique inversion exists if quasi-steady flow profiles can be obtained under two different conditions, and if a measurable difference in the open borehole water level is given between the two conditions. If there are N water-producing zones, the data set provides the 2N measurements needed to solve for the set of 2N variables (T, transmissivity, and H, hydraulic head) in each zone. Such a test was completed at Faribault, where one condition was ambient flow, and the other pumping at about 2 gpm. Measured drawdown stabilized within minutes at about 0.1 ft, and there were obvious differences in the flow regime between these two conditions. Thus, this set of flow log data provides the basis for quantitative analysis of aquifer properties.

A preliminary set of flow data was obtained by making stationary measurements at about ten representative depth stations (fig. 5). Complete flow profiles were then obtained under the two different flow conditions by trolling up at about 10 ft per minute "against the grain" of the predominantly downward flow. The nominal flow scale on these logs does not represent borehole flow. The scale gives the volume flux through the measurement throat of the logging tool while the probe is being trolled up the borehole. Thus, the "true" flow in the borehole (Q) is related to the measured flow (Q_m) by the equation:

$$Q = AQ_m - B \tag{1}$$

where A and B are constants that correct for the "leakage" of water around the probe, and for the trolling speed superimposed on the flow distribution.

Even before transforming the data, the flow logs in figure 5 indicate that there are seven different water-producing zones, each of which can be related to bedding planes or solution openings given by the televiewer log. The Q_m data are converted to Q values by comparing the flow logs in figure 5 with a set of data obtained with the flowmeter held stationary at a series of points in the borehole (fig. 6). A few stationary points (10 points for the ambient flow profile and 15 for the flow profile made while pumping) are not sufficient to effectively characterize the complex distribution of flow. But these points do not have the effects of trolling added to the measurement. The stationary flow values (Q_s) are related to total flow (Q) by a multiplication factor:

$$Q = CQ_s \tag{2}$$

In this expression the constant C multiplies the fraction of the flow passing through the measurement throat to account for the additional flow bypassing the throat in the annulus around the probe. A value for C can be obtained by making measurements in the bottom of casing during pumping where the total borehole flow is known to be close to 2.0 gpm. The value of C is defined by measuring flow under the pump within the casing with the probe stationary. In this example, the scatter of about 0.3 gpm is greater than the typical 0.1 gpm scatter because the flexible disk used to restrict flow in the annulus around the probe measurement section was removed at the beginning of logging. But even under the best of conditions, the "leakage" of flow around the probe introduces measurement error significantly greater than the nominal accuracy derived from flow column experiments.

When the stationary data points are converted to total borehole flow, these points do not effectively define the flow distribution. There are just not enough of these points to define the "true" flow profile in a situation where there are seven different inflow and outflow zones. The errors in estimating inflow or outflow at each zone account for the large negative values in the right-hand column for the Faribault borehole in table 2B. But the values of the constants A and B in equation (1) can be adjusted until the stationary flow points "pin down" the flow distributions. This is done in figure 6. In this way, the detailed flow distribution given by the trolled logs in figure 1 can be effectively calibrated. The resultant estimates of inflow and outflow at each of the seven zones (table 3) are derived from both stationary and trolled measurements, combining the vertical resolution of the trolled data with the flow measurement accuracy of the stationary data.

A rough estimate of the relative transmissivity of each of the seven zones can be made by using the flow profiles in figure 6 to estimate the amount of water entering the borehole under the two flow conditions. In this analysis, negative inflow represents outflow. The amount of water entering under any condition depends on the product of the zone transmissivity and the difference between zone hydraulic head and open borehole water level. The open-borehole water level adjusts itself to approach the water level in the most permeable zone, so that the hydraulic gradient driving flow from that zone into the borehole is generally less than the gradient driving flow into or out of other zones. However, if the inflows under two different conditions are subtracted, the hydraulic head dependence factors out, and the differences are proportional to zone T. Doing this for the seven zones in figure 6, we get the results listed on the right hand side of table 3.

One test of consistency is that the total inflow under ambient conditions vanishes, and the total inflow under pumped conditions is 1.8 gpm (within measurement error of the known 2.0 gpm pumping rate where the magnitude of the measurement error of about ±0.30 gpm is estimated from the scatter in the flow log data between inflow zones). The data are inconsistent, in that the difference for zone 5 is negative, which is hydraulically impossible. We interpret this result as simply an artifact of the measurement error. The subtraction of two quantities which are determined from the differences of other quantities acts to amplify measurement error. Thus, the analysis suggests that zones 1, 4, and 7 are an order of magnitude more permeable than the other zones. The percentages for the other four zones are effectively too small to quantify.

A more quantitative approach is to use a hydraulic model to predict the flow for the ambient and pumped conditions. With seven zones, this is a formidable problem. The idea is to find the one set of T and H values for the seven zones which gives the measured flow profiles at the measured drawdown. One has to guess 14 different parameters by trial and error to obtain the fit. This was accomplished by first ignoring all but the three main zones. When an approximate fit was obtained, the other four zones were added. A reasonable fit results with the parameters listed in table 4 and all flows predicted by the model fall within the ±0.30 gpm measurement error. Note that the fit requires matching both flow profiles and the measured 0.1 ft drawdown, as indicated in table 4. These results indicate that the upper three water-producing zones are part of a single large-scale aquifer compartment. Drawdown is communicated to the aquifer via the 170-190 ft zone. Hydraulic-head gradients drive flow downward into that zone from above, and upward into that zone from below.