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Borehole flowmeter applications in irregular and large-diameter boreholes

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Abstract

High-resolution flowmeter measurements such as those obtained with heat-pulse and electromagnetic flowmeters are often analyzed to produce in situ permeability profiles of heterogeneous aquifers. However, the borehole environment exerts a strong influence on the accuracy of flow log data and its interpretation. As many as five different types of corrections need to be applied to many flow-log data sets: (1) Adjustments to differentiate between very low-flow and no-flow environments; (2) normalization to account for changes in the magnitude of the flow regime attributed to changes in pumping rate or relaxation of drawdown when measurements are made during water-level recovery; (3) multiplication by a constant factor to account for leakage around the flowmeter measurement section related to ineffective sealing of the annulus by packers or flexible-disk diverters; (4) correction of continuous flow logs collected while trolling by adjusting the zero-point and scale of the log to match a few stationary flow data points; and (5) suppression of the effects of diameter variations on trolled flow logs by collecting data with an under-fit diverter and developing calibration curves representing bypass factor as a function of local borehole diameter. Specific examples of these corrections applied to heat-pulse and electromagnetic flowmeter data sets are given for logs obtained in open boreholes in igneous, metamorphic and sedimentary bedrock, and in screened boreholes in unconsolidated sediments. Scatter in flow measurements related to the efficiency of diverter operation in the field act to effectively limit the permeability detection capability of both heat-pulse and electromagnetic flowmeters to about two orders of magnitude regardless of the dynamic range and accuracy of either flowmeter as demonstrated in smooth-walled calibration tubes.

Keywords: Flowmeter logging; Permeability measurement; Well hydraulics

1. Introduction

Most geophysical logs provide measurements of physical properties that are indirectly related to the hydraulic properties of formations, so that these logs have to be interpreted to give estimates of porosity, permeability or water quality. Borehole-flow logs are an exception to this general statement because flow logs give data that can be directly related to the hydraulic properties of formations (Hill, 1990; Molz et al., 1989; Paillet et al., 1987). Recently developed high-resolution flow logging equipment such as the heat-pulse (Hess, 1986) and electromagnetic (Molz et al., 1994) flowmeters can measure vertical flow in boreholes at total discharge rates of a few liters per minute. Measurements made with these flowmeters can be used to generate permeability profiles in situ using such low pumping rates that there is little

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drawdown and turbulent flow losses do not have to be considered (Paillet, 1998, 2000a).

The availability of high-resolution borehole flowmeters has led to a proliferation of theoretical studies of the interpretation of borehole flow profiles (Molz et al., 1989; Lapcevic et al., 1993; Kabala, 1994; Rudd and Kabala, 1996; Paillet, 2000b). All of these studies assume that the flowmeter data consist of profiles of vertical flow in the borehole with a minimum of measurement error. Changes in vertical flow rate between measurement stations can then be related to inflow or outflow from the borehole under the given hydraulic conditions. Small measurement errors are introduced by scatter in the measurement of flow through the cylindrical measurement sections of the flowmeter probes. Additional scatter is introduced by the flow that leaks around the packers or flexible diverter disks used to seal the annulus between the flowmeter and the borehole wall. Numerous flowmeter studies stress the importance of making flow measurements in boreholes where there is a small annulus width and where smooth borehole walls allow effective sealing of the annulus with packers or flow diverters (Hsieh et al., 1993; Long et al., 1996).

Restriction of flow measurements to boreholes where small diameter and smooth walls allow effective performance of the flowmeters would insure collection of high-quality data, but practical situations routinely arise where information is required from large-diameter, rough-walled boreholes or production wells. Logistical problems related to pumps and well access, or hydraulic-head fluctuations produced by interference from adjacent wells, may make it impossible to make flow measurements under quasi-steady conditions, which further complicates the flow logging. Flow profiles obtained under such conditions are difficult to interpret, and no hydrologist would want to design flow tests for these applications. The only rationale for running flow logs in such boreholes is the need to obtain answers to pressing questions, or to take advantage of the only boreholes that happen to be available. This paper discusses the various correction techniques that can be applied to at least partially remove these errors, illustrating these corrections with examples using flow data obtained in open boreholes in igneous, metamorphic and sedimentary bedrock, and in screened boreholes in unconsolidated sediments.

2. Borehole-flow corrections

Five different classes of corrections are routinely applied to data sets collected with the high-resolution flowmeters. Each of these corrections is defined and discussed in this section of this paper. Because these corrections are often difficult to understand without specific examples, a subsequent section of this paper presents a series of concise case studies where the corrections are illustrated by example.

2.1. Zero-point correction

Although the heat-pulse and electromagnetic flowmeters can theoretically measure flow as small as 0.05 l/min, both devices can give spurious measurements under very low or no-flow environments. The heat-pulse flowmeter can produce a positive (upflow) response of 0.01–0.05 l/min caused by the buoyancy of the heat pulse in a weak-downflow or no-flow environment. The most conservative approach is to suspect that all nominal upflow measurements less than 0.05 l/min are buoyancy driven and delete these data from the record. The suspect data points are replaced by 0.00 in the data set and are assumed to represent depth stations where flow is too small to measure. In some situations, the log analyst can be selective and edit out only those weak positive flow data points that are not consistent with other supporting information. For example, if the pumping rate is doubled and the measured upflow is increased to a value that is too large to suspect, the analysis might assume that a real flow value has been amplified by the pumping. If the increase in pumping has essentially no effect on the suspect value, then the measurement can be attributed to buoyancy in an otherwise stagnant fluid column.

The electromagnetic flowmeter has a very different low-flow response, where flow is continuously measured, but the measurement can vary by as much as 0.10 l/min over the measurement period. This measurement “drift” can make it difficult to define a zero-point for the flow response. The measurement drift can be minimized by allowing the probe to stabilize at borehole conditions for at least 15 min before the start of data collection. The only way to remove errors is to repeatedly make measurements where there is no flow and subtract the “zero-point offset” from the data. This is not always easy to do, because there may be ambient cross-flow between zones in the borehole, or there may be small water level adjustments causing water to move up into or down out of casing. In many situations, the log analyst is continuously learning about the nature of borehole flow regime during the logging activities. The simplest approach is to make a number of measurements in locations where there is likely to be a stagnant fluid column, such as in casing and just above the bottom of the borehole. After logging is complete, the assumed no-flow conditions in these sections of the borehole can be verified. The measured flow response in those zones considered to satisfy the no-flow assumption can be averaged to give an estimate of the zero-flow bias in the data set. A drift of as much as ± 0.05 l/min for nominal flow through the probe measurement section is not unusual. This value can then be subtracted from all the flow measurements to eliminate the zero-flow bias from the data before other corrections are applied.

2.2. Flow normalization

Under ideal conditions, borehole-flow profiles are obtained under quasi-steady conditions. In practice, various circumstances can cause departure from the steady pumping conditions. Occasionally, the pumping rate is too large for borehole capacity, and flow logs are obtained as the borehole recovers from the initial steep drawdown. Sometimes, the pump is accidentally turned off and pumping resumes at a slightly different rate for the rest of the test. Occasionally, well interference effects cause borehole flow conditions to change continuously with time. In these situations, the flow measurements can be normalized by expressing the flow at any station as a percent of the total flow in the borehole at the time the measurement was taken. The normalization can be made by using the known pumping rates during any given measurement period, as long as care is taken to insure that quasi-steady conditions have been established by monitoring drawdown. In either case, normalization is needed to distinguish changes in the flow between measurement stations that are related to inflow or outflow, from those changes in flow over time caused by the changes in total borehole flow.

There is one important exception to the use of flow normalization. If there is significant cross-flow in the borehole between water-producing zones, flow data cannot be normalized. Flow normalization is based on the assumption that inflow to the borehole is proportional to total borehole discharge or total drawdown. When there is a vertical hydraulic head gradient, the inflow is proportional to the product of head difference driving the flow into the borehole and zone transmissivity, so the flow normalization assumption is violated.

2.3. Flowmeter bypass

The flow measurements given by the heat-pulse and electromagnetic flowmeters represent the flow passing through the cylindrical measurement section on the probe. In theory, this is the entire borehole flow because the annulus between the borehole wall and the probe is sealed with a packer or a flexible-disk diverter. The seal is rarely perfect and some flow will pass around the flowmeter. The flowmeter response, in pulse travel time for the heat-pulse flowmeter and millivolts in sensor response for the electromagnetic flowmeter, is calibrated in discharge units in laboratory flow columns. In the field, the nominal discharge given by either flowmeter needs to be checked against a known discharge. This can be done by comparing the measured flow with known pumping rate under quasi-steady conditions, such as when the flowmeter is stationed above all inflow points during pumping. An alternate approach when quasi-steady conditions cannot be maintained is to compare flow measured at a depth just below water level with the measured rate of recovery after pumping stops. In that situation, the combination of known borehole volume and rate of water-level rise can be converted to flow rate as long as there is no inflow cascading into the borehole from above. The measured flow will often be somewhat less than the known flow, especially if the flow diverter has been subject to wear from prolonged use. The ratio of known flow to measured flow gives a bypass factor. All of the measured flows are multiplied by this factor to give a corrected flow profile.

The bypass factor becomes useful in heat-pulse flowmeter experiments where flow rates are beyond the nominal 6 l/min upper flow measurement limit of the probe. If the diverter is reduced in size so that only a small portion of the total flow passes through the flowmeter measurement section, the heat-pulse flowmeter can give useful measurements under flow rates much larger than 5 l/min. The measured flow falls within the 0.05–5.0 l/min measurement window for the probe, but the measurable flow ranges over limits given by the product of those limits and the bypass factor. Although the electromagnetic flowmeter has no theoretical upper measurement limit, commercially available electromagnetic flowmeters have an upper flow limit of about 120 l/min imposed by flowmeter calibration conditions. Increasing bypass allows measurement of even larger flows with the available electromagnetic flowmeters. Effective flow profiles have been reported for cases with a bypass factor as large as 100.0 (Paillet, 2000a) using a version of the heat-pulse flowmeter designed by the U.S. Geological Survey.

2.4. Trolling measurement bias

One effective way to identify the exact depth intervals where water enters or exits the borehole is to measure flow while moving the probe at a steady rate up or down the borehole. The depths where the measured flow changes abruptly can be used to identify the zones where flow enters or exits the borehole. Although trolled flow logs indicate inflow or outflow depths effectively, the trolling velocity biases the flow measurements. The simplest way to remove the trolling bias is to obtain a representative number of stationary flow measurements. The trolled flow can be superimposed on the scatter plot of the discrete stationary measurements. The scale and offset of the trolled logs are then adjusted until the difference between the trolled log and the stationary measurements is minimized. The offset is not enough by itself, because the trolling does more than add a simple translational velocity to the flow measurements. The movement of the probe forces water to "funnel" through the measurement section, causing the flow measurement to be increased by more than simple "plug" flow through the measurement section. The adjustment of both offset and scale factor accounts for this hydrodynamic effect.

2.5. Borehole diameter effects

Variations in borehole diameter allow for various amounts of bypass around the flowmeter during either stationary or trolling measurements. The effect of diameter variations is accentuated during trolling with a diverter, because the diverter forces the entire volume of the borehole to circulate through the measurement section of the probe during the trolling. For example, a reasonable trolling rate of 2 m/min (relatively slow by geophysical well logging standards) in a 15-cm diameter borehole amounts to about 37 l/min of flow. Diameter variations of a few centimeters would superimpose apparent flow changes of as much as plus or minus 15 l/min on this average flow measurement. It would be impossible to identify "steps" of a fraction of a liter per minute attributed to inflow in such a borehole.

One practical approach to trolled flowmeter measurements in a rugose borehole is to use a deliberately under-fit diverter. The gap between the borehole wall and the diverter disk allows a substantial portion of the borehole flow volume to bypass the flowmeter as it is trolled up or down. This bypass substantially reduces the effect of local diameter variations on the flow measurement. At the same time, the under-fit diverter is required to force at least some of the flow into the probe measurement section. Without the diverter, the flow is not effectively "deflected" into the measurement section of the probe.

In situations where the borehole diameter variations are significant, the caliper log can be used to correct for diameter effects. The correction cannot simply be based on the relative ratio of the cross-sectional areas of the annulus around the probe and the inside of the probe measurement section. Such a simple geometric correction does not account for the effects of the shape of the probe and the presence of the diverter on the flow fields as water moves around or through the probe. A practical way to correct for diameter variations is to estimate bypass factors for a particular probe with a particular diverter in various sized columns. These calibration points can be obtained in the field by making measurements above all inflow points at known pumping rates, or using flow columns in the laboratory. During these measurements, it is assumed that the flowmeter is held in the center of the borehole by bowspring centralizers to insure that the flowfield remains cylindrically symmetric. In general, the bypass factor will increase non-linearly with increasing gap between the diverter and the borehole wall. When several such bypass calibration points have been obtained over a given diameter range, the bypass factor for any diameter within that range can be estimated by fitting a second-order polynomial to the discrete calibration points. Then the diameter given by the caliper log can be used to generate a bypass factor for the correction of flowmeter measurements at each depth point in the borehole.

3. Examples of flow log corrections

The application of the corrections used for the heat-pulse and electromagnetic flowmeter logs is best described by reference to specific examples. This section presents a series of case studies selected to illustrate each of the five types of flow log corrections described in Section 4. The examples start with three situations where conditions are close to optimum for flow logging. Subsequent examples extend the log correction methods to examples where conditions are far from ideal for flow log interpretation because of large borehole diameters and irregular borehole walls, but where these boreholes provided the only available access to the aquifer being studied.

3.1. Electromagnetic flowmeter measurements in a crystalline bedrock aquifer

An electromagnetic flowmeter data set from a borehole in granitic schist in New Hampshire illustrates one of the simplest and most straightforward flow interpretation problems (Fig. 1). No measurable flow was detected in the borehole under ambient conditions, and the caliper log showed that the borehole had relatively smooth walls of almost exactly the same diameter as the inside diameter of the surface casing everywhere except where a few fractures intersected the borehole wall. The flowmeter data in Fig. 1 were obtained with a probe using a new diverter cut to be slightly larger than the inside casing diameter, so that laboratory flow calibration data were expected to apply to this data set. Examination of the data verifies that the flow measured in casing during pumping agrees with the measured pump discharge rate of 17.5 l/min. If the flow data in Fig. 1 are then interpreted so as to infer the inflow at various depths in the borehole, the results indicate a

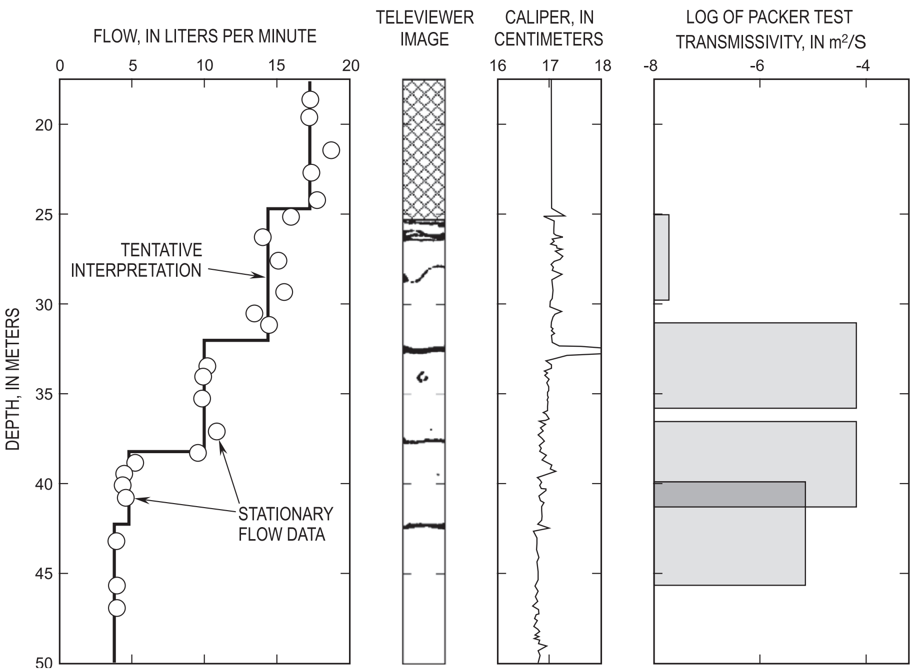

Fig. 1. Electromagnetic flowmeter data for a crystalline-bedrock borehole in New Hampshire illustrating the effect of the rough borehole wall compared to the smooth inside of casing on flow measurements where there is no significant difference between inside diameter of the casing and the average borehole diameter, and where straddle-packer hydraulic tests indicate there is no significant transmissivity near the bottom of casing.

significant amount of inflow within a meter of the bottom of casing.

The borehole flow interpretation in Fig. 1 was checked by performing straddle-packer injection tests over intervals designed to straddle each of the possible water-producing zones. These results verified the flow interpretations everywhere except in the interval near 25 m in depth. The packer test data show that the transmissivity of the zone at the bottom of casing is more than three orders of magnitude less than that of the other zones, while the interpreted inflow from the 25-m zone is several times greater than the interpreted inflow for the 42-m zone. The discrepancy is almost certainly caused by the effect of borehole wall conditions on the flow measurement. Even though the measurements were made with an unworn diverter and even though the open borehole has the same nominal diameter as the inside of casing, the roughness of the hammer-drilled borehole wall had enough of an effect on the operation of the diverter to affect flowmeter calibration. If the flowmeter data are corrected to be consistent with the straddle-packer test results, then the open-borehole flowmeter data need to be multiplied by a bypass factor of 1.22. This correction accounts for the fact that there is some bypass around the edges of the diverter in a rough-walled borehole above and beyond any diverter leakage in calibration measurements made in a smooth-walled calibration tube. These results indicate that laboratory calibrations of flowmeter measurements almost never apply to real boreholes where relatively small differences in roughness compared to the perfectly smooth walls of laboratory flow tubes can have a significant effect on flowmeter measurements in the field.

3.2. Heat-pulse flowmeter measurements in a crystalline bedrock borehole

Another typical example of flow logging is given for an open borehole in fractured granitic bedrock in North Carolina (Fig. 2). The heat-pulse flowmeter showed no ambient flow in the borehole at the time of logging. The caliper showed a smooth borehole wall with a few openings where fractures intersected the borehole. Flow measurements were made at depth intervals designed to bracket possible inflow points during steady pumping. The original flow measurements listed in Table 1 had to be corrected to account for the bypass of flow around the diverter, for changes in the pumping rate after the pump was inadvertently shut off by a circuit breaker and manually restarted, and because flow measurements near the very top of the borehole could only be made after the pump was removed from the borehole. The measurements made during water level recovery during the period when the pump was accidentally turned off, and after removal of the pump near the end of the experiment, were normalized by interpolating the drawdown between periodic water-level measurements using the equation:

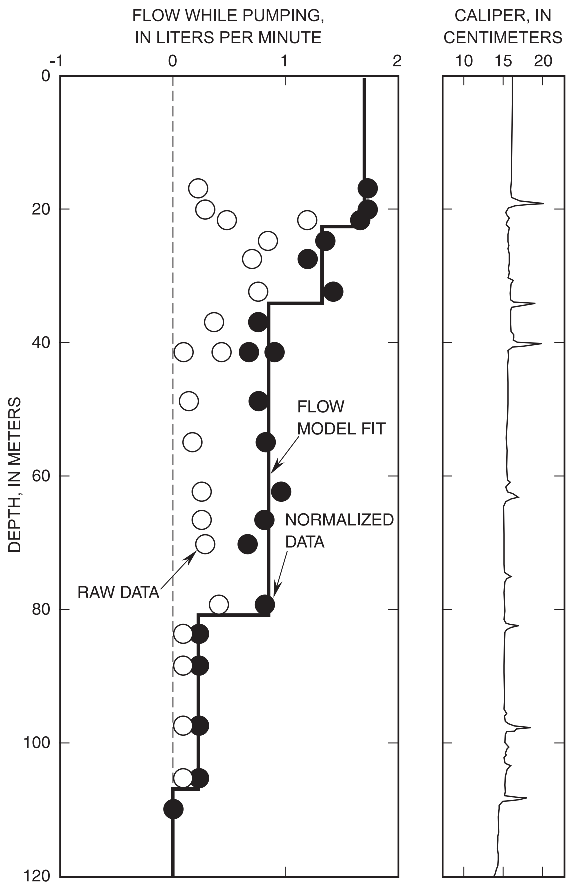

Fig. 2. Heat-pulse flowmeter data profile for a crystalline-bedrock borehole in North Carolina illustrating the raw flow data points, flow corrected for bypass and changes in pumping rate, and flow model fit to the data; model fit parameters listed in Table 1.

$$Q = Q_m D_0 / D_m$$

where Q is the normalized flow measurement, Q_m is the measured flow during recovery, D_m is the interpo-

Table 1
Raw heat-pulse flowmeter data and corrections for the North Carolina bedrock borehole

	Depth station (m)	Drawdown[a] (m)	Measured[b] flow (l/min)	Normalized[c] flow (l/min)	Corrected[d] flow (l/min)
Pump off and removed	14.8	0.16	0.11	0.53	1.06
	16.8	0.19	0.23	0.87	1.74
	19.8	0.35	0.30	0.87	1.74
	21.3	0.43	0.49	0.83	1.66
Pump on at higher rate, drawdown increasing (2.6 l/min)	21.3	1.05	1.21	0.83	1.66
	24.4	0.93	0.87	0.68	1.36
	27.4	0.86	0.72	0.60	1.21
	32.0	0.80	0.79	0.72	1.44
	36.6	0.75	0.38	0.38	0.76
	41.2	0.73	0.45	0.45	0.91
Pump off by accident	41.2	0.24	0.11	0.34	0.68
	48.8	0.29	0.15	0.38	0.76
	54.9	0.33	0.19	0.42	0.84
	62.5	0.39	0.27	0.49	0.98
	66.5	0.46	0.27	0.42	0.83
	70.1	0.65	0.30	0.34	0.68
Steady drawdown (1.75 l/min)	79.3	0.73	0.42	0.42	0.83
	83.8	0.73	0.11	0.11	0.23
	88.4	0.73	0.11	0.11	0.23
	97.5	0.73	0.11	0.11	0.23
	105.2	0.73	0.11	0.11	0.23
	109.7	0.73	0.00	0.00	0.00

[a] Drawdown at the time of each flow measurement estimated by interpolating between discrete drawdown measurements.

[b] Measured flow: average of three or more repeatable measurements, measurements made sequentially from bottom to top of borehole.

[c] Normalized flow: flow measurements normalized to remove effects of temporal changes in overall magnitude of flow produced by increasing drawdown from increased pumping rates, decaying drawdown produced when pump accidentally stopped, or in a deliberate effort to allow logging close to water level.

[d] Corrected flow: flow measurements multiplied by an estimated bypass factor of 2.0 to account for leakage by the flow diverter; values estimated by comparing flow measured in casing above all inflow points (ranging from 0.68 to 0.86 l/min) with known pumping rate (1.75 l/min).

lated drawdown during recovery at the time of measurement and D_0 is the quasi-steady drawdown during the first round of pumping. The measurements made after the pump was restarted were normalized on the basis of drawdown and not on the basis of increased pumping because the water level was changing during the course of the measurement period.

After these corrections were applied to the data set, the flow profile indicated that there was no inflow to the borehole above 22 m in depth. Therefore, the average flow in the interval above 22 m in depth could be compared to the known pumping rate to estimate the bypass factor. The comparison shows that the known pumping rate was almost exactly twice the measured flow in the interval of the borehole above all inflow zones. When multiplied by this bypass factor, the corrected and normalized flow profile clearly indicated four inflow zones during pumping. The Paillet (1998, 2000a,b) borehole flow model was then used to fit this data as shown in Fig. 2, providing estimates of the transmissivity of each of the four zones as indicated in Table 2. Further confidence is added to the interpretation because the four inflow zones are clearly and unambiguously associated with indications of permeable fractures on the caliper log.

3.3. Electromagnetic flowmeter measurements in sedimentary rocks

A somewhat more complicated flowmeter interpretation is given for an electromagnetic flowmeter log from a sedimentary bedrock borehole in eastern Pennsylvania (Fig. 3). The logging in this example was more difficult because the log had to be corrected for zero-point offset, and because there was an abrupt change in borehole diameter in the upper part of the borehole.

Table 2
Results of flow model fit to flow log data sets from North Carolina borehole (data shown in Fig. 2) and Connecticut borehole BGAS-1 (data shown in Fig. 5)

Flow zone (depth in meters)	Zone (m^2/s)	Zone hydraulic head (meters below top of casing)
North Carolina borehole—Fig. 2		
22.0	5.9×10^{-6}	14.30
34.0	7.7×10^{-6}	14.30
84.0	10.2×10^{-6}	14.30
108.0	3.7×10^{-6}	14.30
Connecticut borehole—Fig. 5		
16.8	2.0×10^{-5}	5.95
32.0	4.0×10^{-5}	6.87
39.8	1.3×10^{-5}	6.87

Although the caliper log indicated a relatively smooth borehole wall, the televiewer log indicated a number of fractures, bedding planes and possibly permeable sandstone beds that might be associated with inflow to the borehole. A total of three boreholes were logged at this site and two of them were logged at different pumping rates (Table 3). All three boreholes were similar, and all were logged with the same flowmeter and diverter. For this reason, it was considered to use ‘‘global’’ rather than ‘‘individual’’ values for zero-point offset and flowmeter bypass factor. In this analysis, ‘‘global’’ refers to averages of offset and bypass factors for all of the boreholes together, whereas ‘‘individual’’ refers to those values for each borehole. The global factors were used in this analysis because logging conditions were identical for all logging, and the average of the corrections for all logging runs was considered to be more accurate than the values from any single run. Thus, a zero-point offset of -0.23 l/min and a bypass factor of 3.35 were used to correct all of the flow data obtained from the three boreholes.

In addition to the zero-point and bypass corrections, this data set also includes flow measurements that were corrected for an abrupt step in borehole diameter from 15 to 20 cm produced by a change in bit size during drilling. Flow measurements made in the larger-diameter intervals of these two boreholes cannot be directly compared to measurements made in the rest of the borehole. To determine correction factors, flow measurements were made as close to the diameter change as possible. It was considered unlikely that flow entered or exited precisely at the diameter change, and no such inflow point was indicated by either televiewer or caliper logs. Comparison of flow above and below the diameter change (after correction for bypass and zero-point offset) indicated that the corrected flow in the enlarged interval of borehole had to be multiplied by an additional factor of 3.3 to account for the much greater flow bypass in the larger borehole diameter interval. This additional correction was also a ‘‘global’’ value derived from the average of the ratios of flow below and above the diameter change for the two boreholes where such changes occurred. After all of these corrections were made, the flow profile was plotted for comparison with other logs to indicate the nature of the inflow zones and could be fitted to a flow model to estimate the transmissivity of the inflow zones. Also note that the relatively ‘‘soft’’ diverter used to obtain the flowmeter data in Fig. 3 resulted in a bypass factor greater than 3.0, but had the positive effect of making the flowmeter relatively insensitive to the differences in borehole wall roughness between the open borehole and the inside of steel casing.

3.4. Trolled heat-pulse flowmeter measurements in a basalt aquifer

Borehole flow log interpretation becomes complicated when there are long intervals of open borehole and numerous possible fracture or bedding plane inflow or outflow points (Fig. 4). In this example, heat-pulse flowmeter data were obtained in an observation borehole adjacent to a municipal wellfield in Hawaii (Paillet and Hess, 1995). The flow was measured during steady pumping at about 100 l/min. The nominal pumping rate was much greater than the nominal upper limit for flow measurement with the heat-pulse flowmeter used with a borehole packer to completely block the annulus around the probe. For this reason, and to allow measurements to be made while trolling at a steady rate, the borehole was logged with the packer partially deflated so as to only partially block the annulus around the probe. The flow log was corrected for bypass and trolling bias in two steps. First, repeat probe response with packer inflated and partially deflated were measured in the lower part of the borehole where the upflow induced by pumping was small enough to fall within the measurement range for the probe with the packer inflated, and near the lower limit

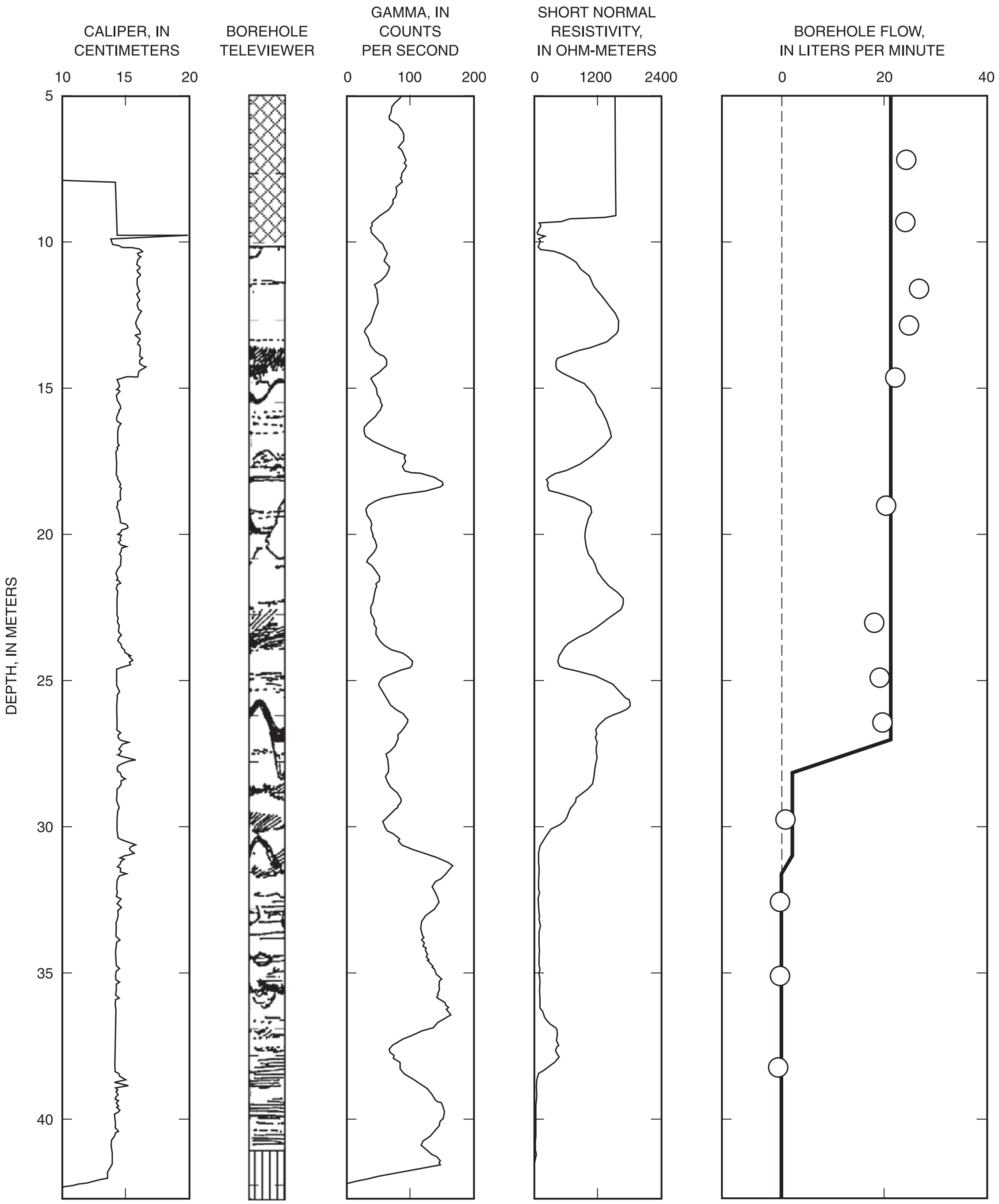

Fig. 3. Electromagnetic flowmeter data profile for a bedrock borehole in Pennsylvania, showing flow data corrected for bypass and flow model fit to the data; other geophysical logs shown for comparison.

Table 3
Values used to estimate zero-point offset and bypass factors for the three Pennsylvania boreholes

Borehole number	Pumping rate (l/min)	Drawdown (m)	Zero flow[a] (l/min)	Measured flow[b] (l/min)	Bypass factor
MW-1	Ambient	0.00	− 0.14	–	–
	12.59	0.12	− 0.24	3.64	3.45
	32.89	0.39	− 0.36	10.58	3.11
MW-2	Ambient	0.00	− 0.19	–	–
	10.96	0.06	− 0.32	3.12	3.52
	35.72	0.18	− 0.23	10.70	3.34
MW-3	Ambient	0.00	− 0.12	–	–
	22.19	1.16	− 0.21	6.67	3.33
Average	–	–	− 0.23	–	3.35

[a] Flow measurement in zone below all inflow and within 3 m of the bottom of the borehole.

[b] Flow measured in casing below pump intake after quasi-steady conditions were achieved; values are corrected for zero-point offset.

of measurement for the probe with the packer partially deflated. This indicated an effective upper limit for the flowmeter of about 120 l/min. Then, a few representative measurements were made with the flowmeter configured with the partially deflated packer at representative stations along the borehole. The borehole flow at these depth locations could be estimated using the bypass factor given by the ratio of measurements made with inflated and partially deflated packer, but there were not enough of these data points to define the exact location of inflow zones along the borehole. However, these few data points could be used to adjust the scale on the trolled measurements as illustrated in Fig. 4. The adjusted log combines the accuracy of the stationary flow measurements in determining the amount of water entering in each zone with the accuracy of the trolled log in defining the precise locations at which flow entered the borehole.

3.5. Electromagnetic flow measurements in a crystalline bedrock borehole with significant ambient flow

The presence of significant ambient flow in boreholes adds an additional complication to borehole flow logging (Fig. 5). In this example from central Connecticut, the average zero-point offset was − 0.12 l/

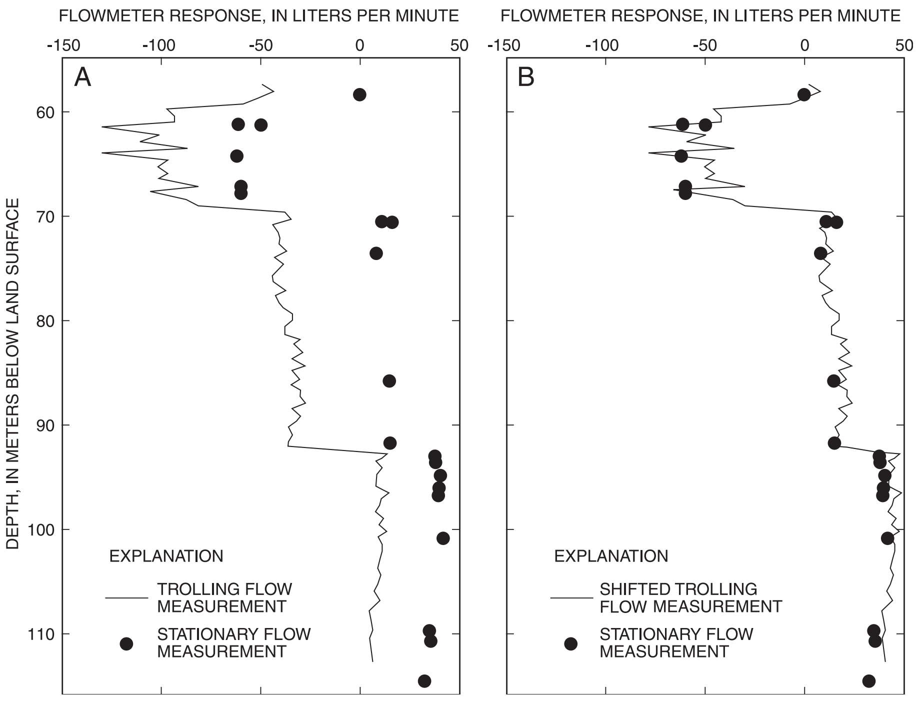

Fig. 4. Heat-pulse flowmeter data profiles obtained while trolling in a basalt-bedrock borehole in Hawaii, illustrating the use of a few stationary measurements to remove the effect of the flow measurement bias introduced by probe movement along the borehole (from Paillet and Hess, 1995).

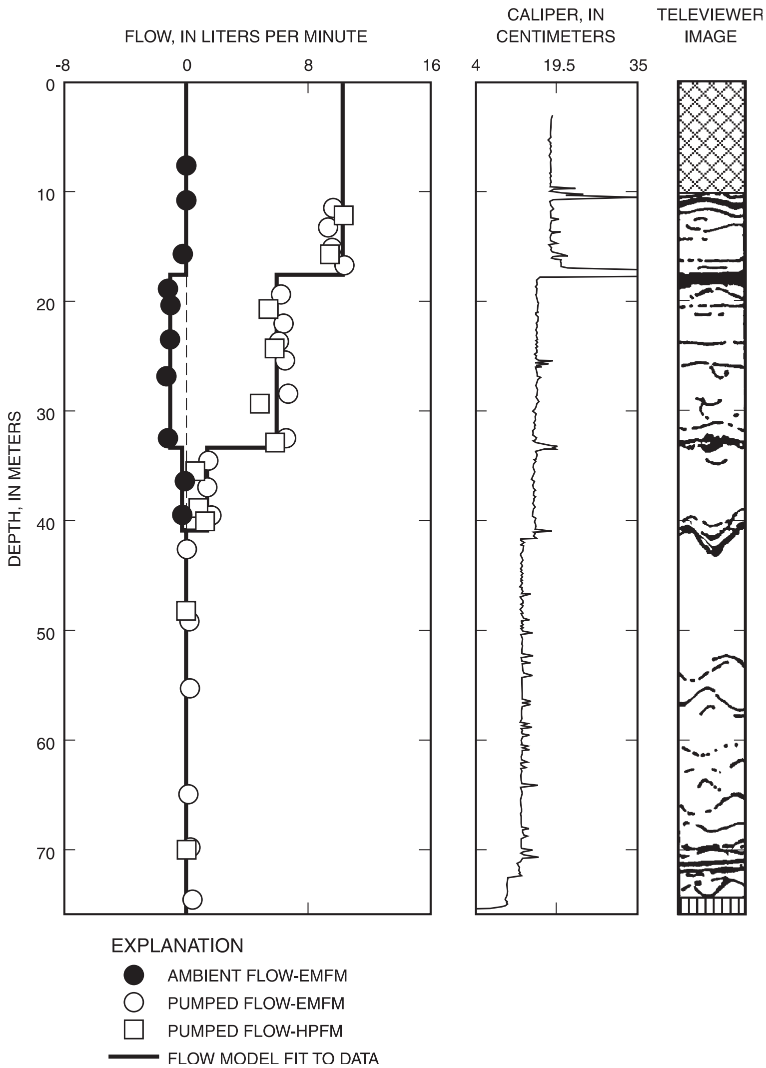

Fig. 5. Electromagnetic flowmeter data profile for a crystalline-bedrock borehole in Connecticut with significant flow under ambient conditions, showing model fit to corrected data for both ambient and steady pumping conditions; heat-pulse flowmeter data shown for comparison and model fit parameters listed in Table 1.

min and the bypass factor was estimated to be 3 on the basis of values determined for a set of three similar boreholes. The corrected flow data are fitted to a flow model in Fig. 5, giving estimates of transmissivity and hydraulic head for each zone as listed in Table 2. In this situation, the flow modeling requires that the transmissivity and hydraulic head of each water-producing zone be adjusted until the predicted and measured flow profiles agree for both pumping and ambient profiles.

In situations such as that illustrated in Fig. 5, trolled flowmeter logs can be used to indicate precisely where fractures shown on the acoustic televiewer log are associated with inflow during pumping. The challenge in the interpretation of such trolled logs is the need to identify small shifts in the log associated with inflow within the often larger variations produced by borehole diameter changes. Although the caliper logs for the Connecticut boreholes showed relatively few borehole enlargements and no abrupt changes in borehole diameter, trolled flow logs in these boreholes provide an illustration of the significant effects of diverter size in suppressing borehole diameter effects (Fig. 6). Trolled flowmeter measurements at the slow rate of 1 m/min with a full-sized diverter produced a flow log where the effects of the inflow zone are difficult to identify. In contrast, flowmeter measurements made at double the logging speed with an under-fit diverter produced a significantly less noisy flowmeter log where the "steps" in the profile at the two inflow zones are more readily recognized within the noise attributed to the borehole diameter variations.

3.6. Heat-pulse flowmeter measurements in open boreholes with major diameter variations

Most logging with the heat-pulse and electromagnetic flowmeters is conducted by making stationary measurements at carefully selected depth stations in boreholes where caliper logs show that the diameter is appropriate for the flowmeter calibration being used. In situations where there is a large amount of flow, the heat-pulse flowmeter range can be extended by using an under-fit diverter. In that case, the upper limit of flow detection will be given by the 6-l/min limit of the probe measurement section multiplied by the bypass factor determined by probe calibration. However, there are some probes where the caliper log indicates numerous large changes in borehole diameter so that one single bypass factor cannot be applied to the data (Fig. 7). In this example from an off-line water-production well in the Kuwait desert, the upper part of the borehole was lined with steel casing and inflow occurs through discrete well screens. In the lower part of the borehole, major washout zones and sharp fluctuations in diameter cause a conventional spinner log to be nearly impossible to interpret.

Heat-pulse flowmeter measurements were made in the Kuwait borehole using a 15-cm diameter diverter to make stationary measurements in an open borehole

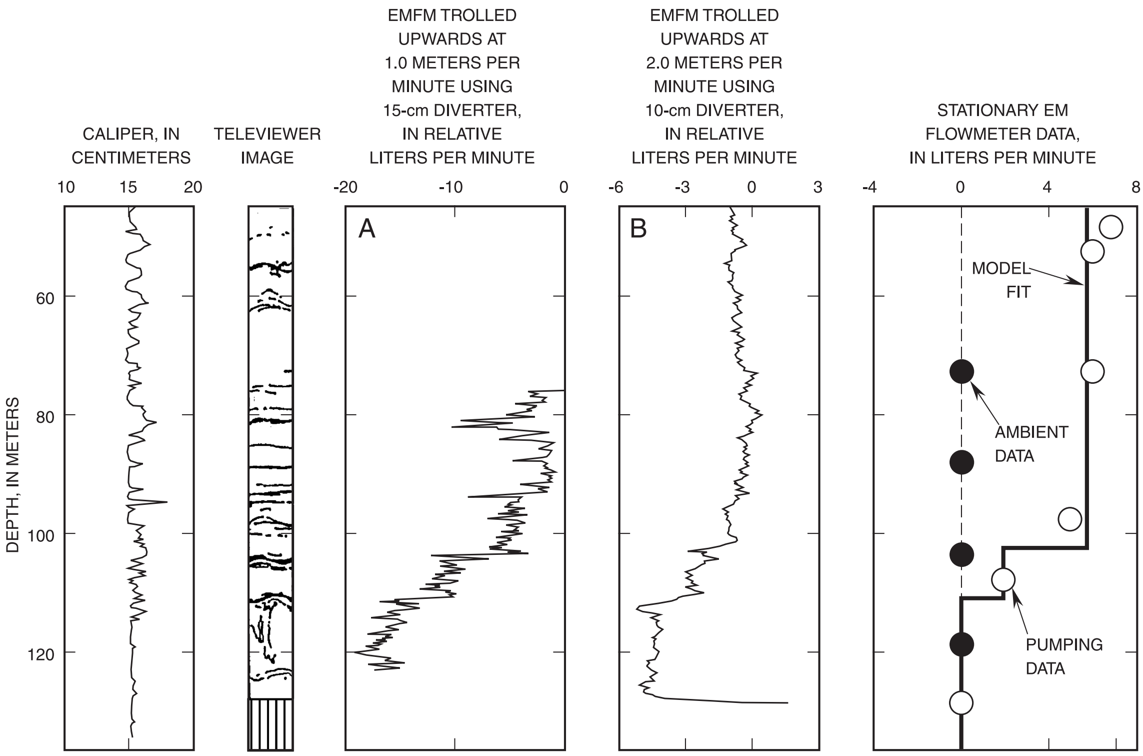

Fig. 6. Comparison of electromagnetic flowmeter data profiles in a 15-cm diameter crystalline-bedrock borehole in Connecticut made, while (A) trolling at about 1 m/min with a full-sized diverter and (B) trolling at about 2 m/min using a 10-cm diverter; caliper, televiewer image and stationary flow data shown for verification of the interpretation.

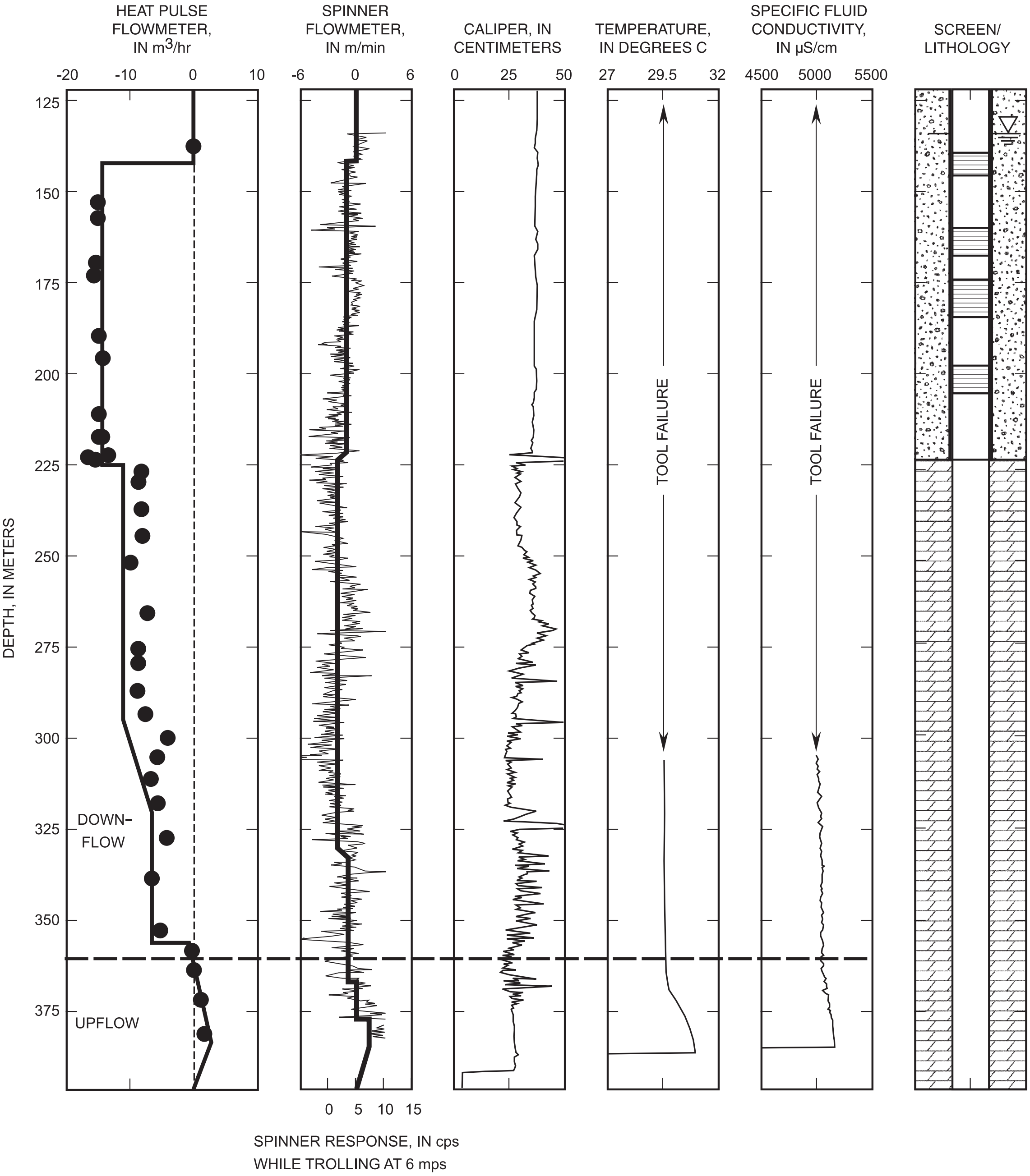

Fig. 7. Heat-pulse flowmeter data obtained with an under-fit diverter in a large-diameter production well under ambient conditions in Kuwait; the flow data were calibrated using a bypass factor estimated from the curve in Fig. 8 and compared to a spinner flow log run at approximately the same time.

ranging from 20 to more than 50 cm in diameter. A single bypass factor could be used to correct the measured borehole flow in the upper 25-cm diameter cased interval. In the lower open-borehole interval, no single bypass factor would be appropriate. However, several bypass calibrations were available for this particular probe with a 15-cm diverter (Fig. 8). Estimates of the bypass factor for any diameter value over the range of these calibrations were made by fitting a second-order polynomial to the discrete data points. Then, the stationary flowmeter data points in the open borehole interval in Fig. 7 were multiplied by a bypass factor given from Fig. 8 for the appropriate value of borehole diameter given by the caliper log. After calibration of the heat-pulse flowmeter data using this method, the interpreted borehole flow profile is generally consistent with the much noisier spinner flowmeter log from the same borehole. The one prominent exception is the interval just below the bottom of casing where the reduction in the diameter of the borehole appears to show acceleration in the downflow whereas the diameter-corrected heat-pulse flowmeter data indicate significant outflow into an opening at the top of the open borehole interval.

3.7. Trolled electromagnetic flowmeter measurements in irregular boreholes

In the worst possible flowmeter logging situations, the borehole wall is so irregular that flowmeter movement in the borehole is difficult. In deep boreholes with such irregular walls, the probe catches on "ledges" and this process allows depth errors of several meters or more to build up in the log even when great care is used moving the probe up and down. With the possibility of such errors combined with the effects of large diameter changes on the measured rate of vertical flow, it is impossible to find smooth intervals for flow measurement or to assign a diameter estimate to any particular depth station. Therefore, the flow log example from a deep observation borehole in Honolulu, HI in Fig. 9 represents one of the most difficult flow log interpretations. The flow logs were obtained by trolling the electromagnetic flowmeter upwards at about 6 m/min under normal conditions with the adjacent wellfield producing at a total rate of about 600 m^3/h, and afterwards under an accelerated pumping rate of about 1100 m^3/h. The flowmeter was equipped with a 20-cm diverter for use in this nominally 25-cm diameter borehole. The fluid column resistivity log for this borehole indicated strong upward flow because the log showed intervals of constant temperature and fluid column resistivity separated by abrupt steps at possible inflow or outflow points, consistent with the upward hydraulic head gradient implied by the production from adjacent supply wells. Although the most effective flow logging would have resulted from trolling downwards with the probe moving "against" the flow, borehole conditions prevented downward logging, and the borehole was logged by trolling upwards under the two different wellfield-production conditions.

In spite of these difficult conditions, the electromagnetic flowmeter log does show changes in flow that are associated with steps in the fluid column resistivity profile. The two flow logs in Fig. 9 were recorded in the field in units of flow through the flowmeter measurement section during trolling (bottom scale in the figure). Because the probe is being moved upwards

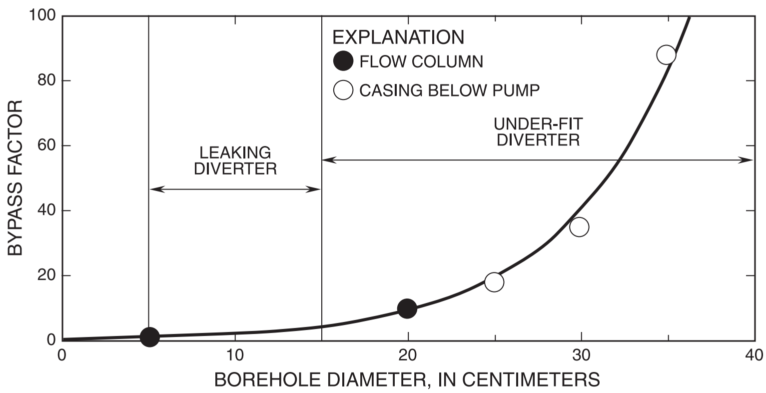

Fig. 8. Flowmeter calibration curve giving bypass factor for a heat-pulse flowmeter equipped with a 15-cm diameter diverter; the curve was constructed by fitting a second-order polynomial curve through a series of data points determined for casing or calibration tubes ranging from 15 to 40 cm in diameter.

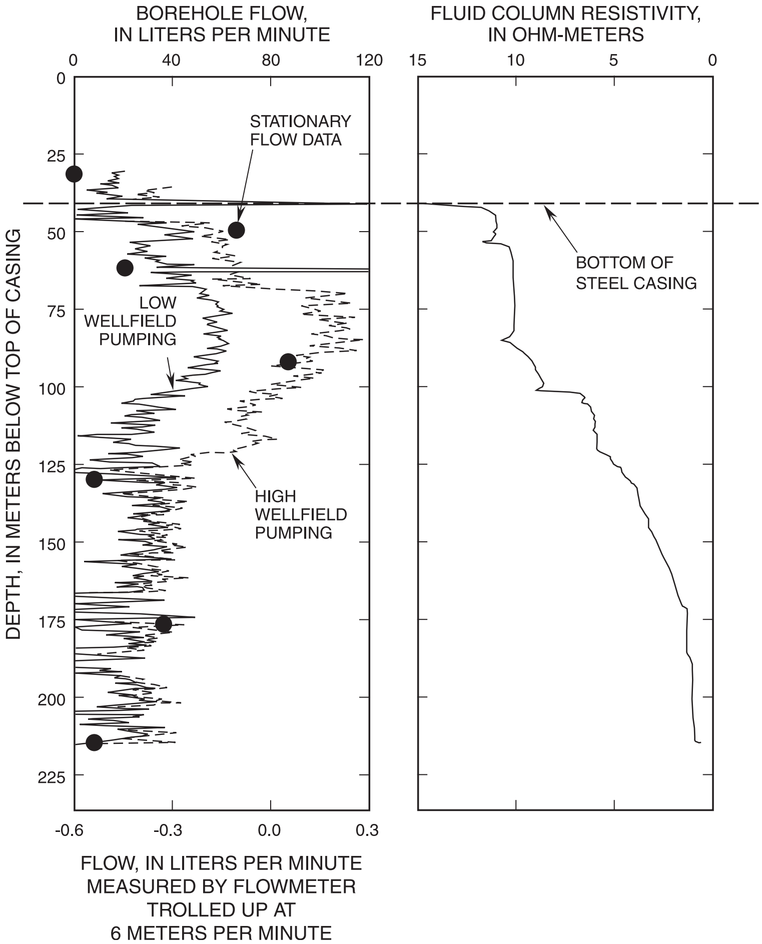

Fig. 9. Flow profiles obtained while trolling upwards at a rate of 6 m/min with an electromagnetic flowmeter equipped with a 15-cm diameter diverter in a nominally 25-cm diameter basalt-bedrock borehole in Hawaii; the two flow profiles were obtained while an adjacent wellfield was producing at rates of 600 and 1100 m^3/h. The flow profiles were calibrated using the flowmeter calibration curve in Fig. 10 to account for bypass for a small number of stationary measurements, and then adjusting the scale of the flow profiles to fit the stationary flow data points (from Paillet et al., 2002).

in the borehole at a rate greater than the upflow, measured flow is generally negative (downward) and becomes less negative in intervals with the strongest upflow. The flow log obtained during the accelerated water production also reflects acceleration in borehole flow caused by that increased pumping. The logs indicate upflow from below 230 m in depth, with water entering in several zones from 200 to 100 m in depth and exiting in two zones between 60 and 30 m in depth. The two outflow zones are interpreted as rubble zones between massive basalt flows. They apparently serve as the aquifer supplying water to the adjacent production wells. The observation borehole provides a connection to deeper-rubble zone aquifers that are not in direct communication with the aquifer supplying water to the wellfield (Paillet et al., 2002).

The flowmeter used to obtain trolled electromagnetic flowmeter logs in Fig. 9 was not calibrated for use in a large-diameter borehole with an under-fit diverter. An approximate field calibration was produced by measuring probe response during trolling at various speeds in the fluid column in casing. Water-level measurements were first made to verify that there was no movement of water into or out of storage in casing. Flowmeter output was then recorded during trolling at a series of constant rates in both the up and down directions. Trolling rates in meters per minute were converted to discharge in liters per minute using the known volume of the casing. Although there are some hydrodynamic differences between the situation where the probe is stationary and the water moves around the probe, and where the water is stationary and the probe moves through the water, the flowmeter calibration in Fig. 10 gives an approximate relation between flow through the measurement section of the flowmeter and total amount of water moving past the probe. There are further problems in using this calibration in the open borehole because borehole diameter varies from 25 to nearly 50 cm. The only rationale for using Fig. 10 to calibrate the flowmeter logs for this borehole is that this is the only calibration available. Because the 25-cm diameter of the casing represents the lower limit of the diameter variations in the open borehole, the calibration in Fig. 10 produces a lower-limit estimate of the flow in the borehole for stationary electromagnetic flowmeter measurements.

The trolled flow logs in Fig. 9 were calibrated by taking a series of stationary measurements during the accelerated pumping measurement period. Because of the possibility of depth errors and the lack of any interval where the borehole diameter is uniform over even a few meters, the depth stations were selected at random. The stationary flow responses obtained at these stations were calibrated using the data in Fig. 10 to estimate the total flow passing the flowmeter. The stationary measurements were then used to adjust the scales of the trolled flow logs in Fig. 9 to give the scale in units of total borehole discharge shown at the top of the figure. As discussed above, this scale probably represents a lower bound on the true flow scale.

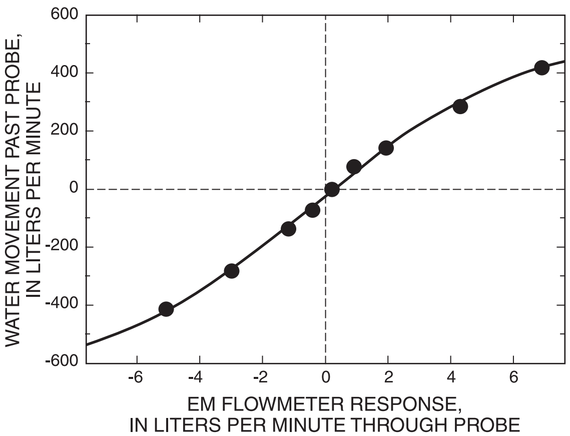

Fig. 10. Calibration curve for an electromagnetic flowmeter operated in a 25-cm diameter casing with a 15-cm diameter diverter; the calibration curve was constructed by comparing probe output with the known volumetric flow moving by the probe while trolling at various steady rates in a stagnant fluid column (from Paillet et al., 2002).

Although the two trolled flow profiles in Fig. 9 seem to represent two quasi-steady flow profiles such as those suggested for use in the flow analysis methods of Molz et al. (1989) and Paillet (2000b), these methods cannot be applied here. The subtraction of inflows method takes the difference of inflows under two different pumping conditions to subtract the effects of vertical differences in background hydraulic head. The method works because the background hydraulic head in each zone is assumed the same for the two pumping conditions. This is not the case in Fig. 9, because the change in water-production rate changes the hydraulic head in the uppermost zones, and the increased head difference between the zones produces the increased flow in the borehole. The flow in Fig. 9 was modeled by assuming that hydraulic-head differences between zones caused the flow measured under the low pumping rate. In that situation, each water-producing zone is assigned a transmissivity (T) and hydraulic head (H) value. The model is used to estimate how much additional drawdown in the upper two zones is required to produce the observed increase in flow, along with the measured change in water level in the borehole (Fig. 11). The flow model was fitted to the data by using the model to "predict" the measured flow in Fig. 9 under the two wellfield-production conditions, where there is a 3-cm lowering of water level in the borehole produced by the increased pumping, for a given set of T and H values, and a given change in water level in the upper two aquifers, E. This procedure is analogous to the model fitting described by Paillet (2000b), except that the model fit is "forced" by lowering the hydraulic heads in the upper zones rather than by pumping from the borehole.

3.8. Heat-pulse flowmeter measurements in fully screened boreholes in unconsolidated sediments

Flowmeter measurements in screened boreholes in unconsolidated sediments can be useful, but the undetermined conditions in the annulus surrounding the screen can have a significant influence on the measured flow. Kabala (1994) and Rudd and Kabala (1996) modeled the flow in such situations by assuming a skin effect where the annular region between well screen and undisturbed formation is characterized by a hydraulic conductivity that is different from that of the formation. In many field applications, boreholes are drilled using drilling mud to maintain an open borehole in unconsolidated formations. A well screen or perforate casing is then installed in the borehole and the mud removed by circulating clean water. Pulsed circulation, surging or compressed air agitation may be used to insure that all mud is removed from the annulus and adjacent formation, and that the formation has collapsed to completely fill any voids. However, it is nearly impossible to verify that the annulus has fully collapsed. In general, the region just outside of the screen is characterized by heterogeneous distribution of hydraulic conductivity that cannot be represented by a simple skin effect. Flowmeter logs obtained in such boreholes need to be interpreted so as to take into account the effects of the conditions in the annulus on the measured distribution of flow in the borehole.

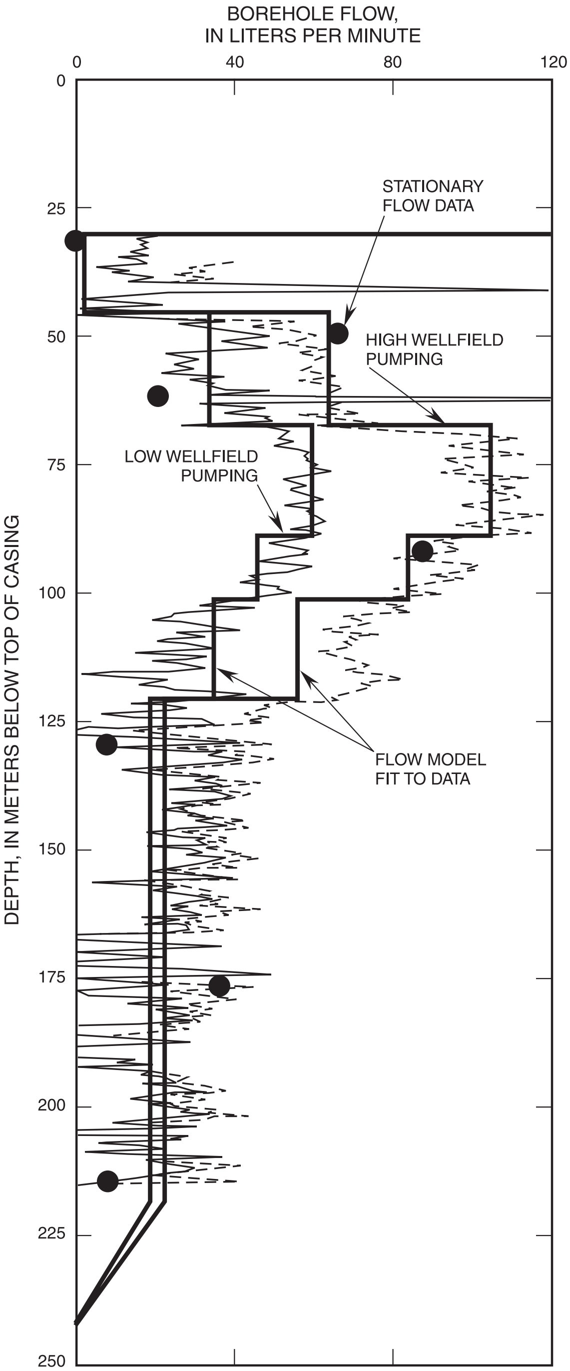

Fig. 11. Flow model fit to the electromagnetic flowmeter data in Fig. 9 and the measured change in water level in the borehole produced by the change in pumping rates between the two quasi-steady flow conditions, based on the assumption that the change in pumping rates in the adjacent wellfield induces the same drawdown in the upper two water-accepting zones while having no effect on the deeper water-producing zones (from Paillet et al., 2002).

A typical example of flow logs obtained under ambient and injection conditions in a screened borehole is illustrated for a borehole in unconsolidated sediments in south Florida (Fig. 12). The flow data indicate ambient upward flow of about 5 l/min, reversed to downflow during steady injection. Water-level changes during injection were too small to measure, so the analysis of the flowmeter data in Fig. 12 is restricted to the subtraction of inflows method (Molz et al., 1989; Paillet, 2000a) to determine relative zone transmissivity as a proportion of total borehole transmissivity. When this method is applied, the very small change in amount of outflow in the upper zone under either ambient or injection conditions can be compared to the complete reversal (outflow under injection compared to inflow under ambient conditions) in the lower zone. This result shows that the lower zone accounts for at least 97% of the transmissivity in the borehole.

Inspection of the flowmeter data in Fig. 12 indicates a rather large amount of scatter in the measurements.

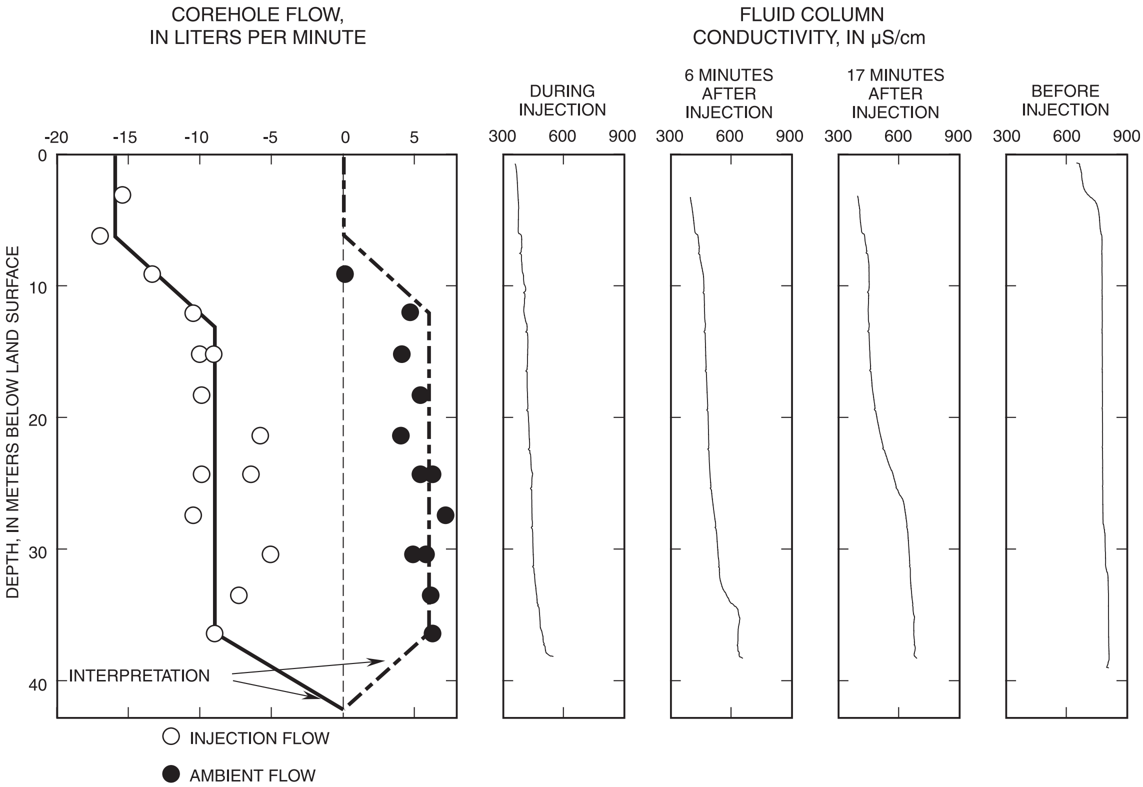

Fig. 12. Heat-pulse flowmeter data profiles under ambient and steady injection conditions in a fully-screened borehole in unconsolidated sediments in south Florida illustrating scatter caused by movement of water in the annulus outside of casing, and showing various fluid column resistivity logs for verification of the flow log interpretation.

This scatter is attributed to incomplete collapse of the annulus, which allows flow to move out into the annulus in some depth intervals. This effect causes local decreases in the flow measured within the screen. Therefore, the flow interpretation in Fig. 12 follows the outer envelope of the data points. The possibility of flow in the annulus supports the interpretation that measured flow is a lower bound on total flow, but additional evidence would be useful in such situations where the data are inherently noisy. Such independent corroboration of the interpretation can be obtained using fluid column logs. In Fig. 12, fluid column resistivity logs are given for ambient and injection conditions, and at two different times during the relaxation from injection back to ambient flow regime. Following the injection and during return to the original ambient flow conditions, the interface between the injected water and the water inflowing from the lower zone can be identified on the logs. The rate of upward movement of the interface can be converted to a volumetric flow by considering the volume of the 12-cm diameter screen. Such a calculation confirms the interpretation of about 5 l/min of upward ambient flow.

The presence of voids behind well screens can make flowmeter log interpretation especially difficult as illustrated in Fig. 13. In this second example from south Florida, steady injection appeared to result in acceleration rather than reduction or reversal of ambient upward flow. Taken at face value, this pair of flow profiles would indicate that a decrease in the hydraulic-head difference driving flow into the lower part of the borehole results in an increase in the flow. Such a condition is hydraulically impossible without allowing for negative permeability. The interpretation of this data set was approached by identifying the set of flow profiles that came closest to the measured flow data while still representing a physically possible flow condition. The presence of upward flow within the

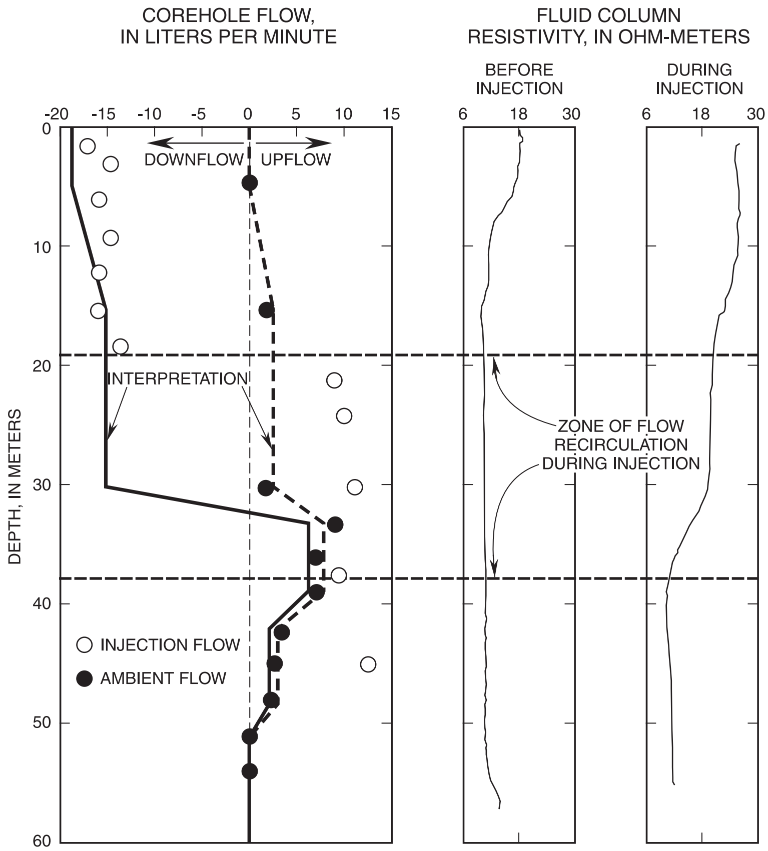

Fig. 13. Heat-pulse flowmeter measurements under ambient and steady injection conditions in a fully-screened borehole in unconsolidated sediments in south Florida illustrating the effects of borehole convection on flow measurements.

screen in an interval where the interpretation shows net downward flow was explained by the possibility of a zone of recirculating water caused by injection with relatively cold and dense surface water during the winter months. The flow interpretation was verified by showing the fluid column resistivity log during injection was fully consistent with an interval of mixing over the 20–40-m depth interval. The flow log interpretation example in Fig. 13 illustrates the importance of obtaining other corroborative data in situations where well screens and an open annulus outside of the well screen complicated flow log interpretation.

4. Dynamic range of borehole-flow measurements

Any publications on borehole flowmeters describe the accuracy of borehole flowmeters in terms of the range of measurable flow, and especially the upper limit of flow that can be detected (Hess, 1986; Molz et al., 1994). Both heat-pulse and electromagnetic flowmeters can measure flow as small as 0.05 l/min in laboratory flow columns. Commercially available heat-pulse flowmeters cannot measure flow greater than about 6 l/min in flow columns, while the electromagnetic flowmeter has no practical upper limit to flow measurements. In practice, the accuracy of flow measurements with either device is limited by the scatter related to the efficiency of diverter operation. For example the scatter in the data points in Fig. 1 (electromagnetic flowmeter data) and Fig. 2 (heat-pulse flowmeter data) is attributed to small changes in the efficiency of the flow diverter and not to scatter in the measurement of flow through the measurement section of either probe.

In field applications with these flowmeters, borehole pumping or injection is usually varied so that the most permeable inflow zone can be readily recognized in the data. In heat-pulse flowmeter applications, the diverter can be reduced in diameter to insure that the magnitude of the flow falls within the measurement range of the probe whenever borehole conditions require measurement of relatively large flow rates. In such applications, the resolution of the flow measurements is controlled by the ability to detect inflow or outflow in the presence of scatter in the data. A typical flowmeter study where there is an extensive set of straddle-packer hydraulic test data for comparison is illustrated in Fig. 14. These results show that the flowmeter profiles could be used to identify all water-producing fractures with the highest order of magnitude of transmissivity, and the majority of fractures with the next highest order of magnitude of transmissivity. Thus, the effective dynamic range of the technique is at most two orders of magnitude. The few water-producing fractures of relatively low transmissivity detected by the flow profiles represent cases where there were no high-transmissivity fractures present to mask their identification. Because the accuracy with which fractures can be detected is imposed by leakage around the diverter and not the inherent resolution of the flowmeter, these results apply to both the heat-pulse and electromagnetic flowmeters.

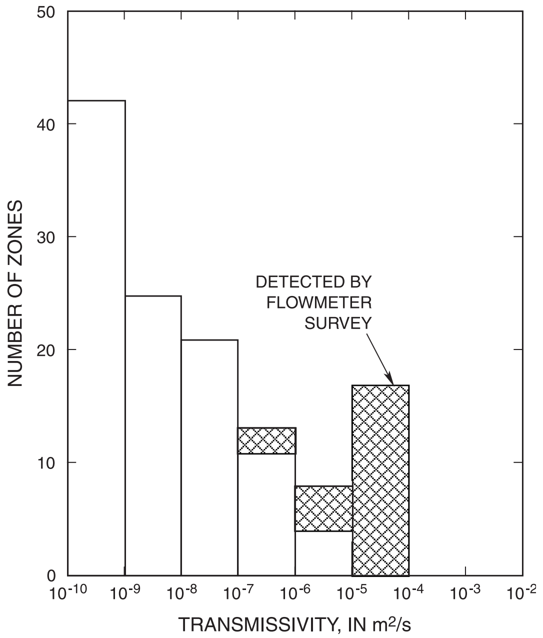

Fig. 14. Comparison of transmissive fractures detected by flowmeter profile analysis with transmissive fractures detected with straddle-packer hydraulic tests for a series of crystalline-bedrock boreholes in New Hampshire (from Paillet, 1998).

5. Conclusions

High-resolution flow measurements such as those given by the heat-pulse and electromagnetic flowmeters are designed to produce permeability profiles of heterogeneous aquifers. However, the borehole environment exerts a strong influence on the effectiveness and accuracy of flow log interpretations. As many as five different types of corrections need to be applied to many flow-log data sets: (1) adjustments to differentiate between very low-flow and no-flow environments; (2) normalization to account for changes in the magnitude of the flow regime attributed to changes in pumping rate or relaxation of drawdown when measurements are made during water-level recovery; (3) multiplication by a constant factor to account for leakage around the flowmeter measurement section related to ineffective sealing of the annulus by packers or flexible-disk diverters; (4) correction of continuous flow logs collected while trolling by adjusting the zero-point and scale of the log to match a few stationary flow data points; and (5) suppression of the effects of diameter variations on trolled flow logs by collecting data with an under-fit diverter and developing calibration curves representing bypass factor as a function of local borehole diameter.

Specific examples of these corrections applied to heat-pulse and electromagnetic flowmeter data sets are given for flow logs obtained at various sites with open boreholes in igneous, crystalline metamorphic and consolidated sedimentary rocks, and with screened boreholes in unconsolidated sediments. In the metamorphic-bedrock examples, borehole walls were generally smooth, and the corrections needed to produce meaningful data sets were straightforward. In one of these applications, the logging was complicated by the presence of strong ambient flow during the logging period. There were numerous fractures indicated by the borehole acoustic televiewer logs. Trolled electromagnetic flowmeter logs were used to verify that inflow during pumping occurred at only a few specific fractures, while most of the others produced no measurable inflow under either ambient or pumping conditions. These logs demonstrated the importance of logging with an under-fit diverter to suppress the effects of even minor changes in diameter on the flow measured during trolling. Two examples of borehole flow in basalt-flow aquifers and the karst example from the Kuwait desert illustrate the use of stationary and trolled flow logs to produce logs that give effective estimates of both the amount of inflow and the depth at which that inflow occurs in a borehole containing many possible inflow zones. The borehole diameter for the second Hawaiian example was far from ideal for flow logging, but obtaining at least some information about aquifer structure was possible by means of approximate field calibration techniques to account for the effect of borehole conditions at the time of logging. Flow logging in fully screened boreholes in unconsolidated sediments offers a special challenge because of the possible effects of voids in the annulus outside of the screen. The two examples from south Florida illustrate that other borehole information can be useful in verifying the interpretation of otherwise ambiguous flowmeter data sets.

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