New Jersey Geological Survey
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Field Tests Using a Heat-Pulse Flow Meter to Determine its Accuracy for Flow Measurements in Bedrock Wells

New Jersey Department of Environmental Protection
Land Use Management

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Field Tests Using a Heat-Pulse Flow Meter to Determine its Accuracy for Flow Measurements in Bedrock Wells

ABSTRACT

The accuracy of water-flow measurements taken with a heat-pulse flow meter (HPFM) in 4-inch and 6-inch-diameter water wells was evaluated in four field tests. The tests are based on comparing fluid velocities induced through pumping and measured at the discharge point with a digital flow meter with fluid velocities in the borehole measured with the HPFM. Two of the tests determined mathematical equations relating heat-pulse arrival times to measured flow rates in the cased part of a 4-inch well tapping a single water-bearing zone. These tests show that on average, HPFM fluid velocity measured using the manufacturer's operating system varies from control values by +50 percent for flow rates ranging from 0.5 to 17.0 ft./min. The manufacturer's built-in time-to-velocity conversion function returns higher-than-expected fluid velocities under low-flow conditions below ~4.5 ft/min and lower-than-expected values above this threshold value. The accuracy of measurement is improved through the application of a power function to derive flow velocities from heat-pulse arrival times above 14-sec and a logarithmic function for arrival times below 14-sec. Use of these equations results in measurement errors of only ± 6 percent relative to the control values.

Two other tests were run in two 6-inch domestic wells constructed with 50 ft of steel casing and otherwise open to bedrock. These tests used a single, controlled discharge rate of ~7.7 ft/min from the cased part of the well to induce flow in the open-hole. Flow velocities in the open and cased intervals were then measured to determine interval flow rates for constructing profile flow diagrams. These tests revealed that the arrival time vs. velocity conversion functions derived from the 4-inch tests return lower-than-expected velocity measurements for the 6-inch wells, ranging from -23 percent to -9 percent relative to the control rate. Nevertheless, applying the power function derived for the 4-inch well improves measurement accuracy by as much as 20 percent with respect to those values reported from the manufacturer's software. Therefore, the Robertson Geologging HPFM is considered to be about 80 percent accurate for determining upward-directed fluid flow between flow rates between about 0.7 to 25 gallons-per-minute in standard, 6-inch bedrock wells after applying the customized arrival time vs. velocity conversion functions.

INTRODUCTION

The New Jersey Geological Survey (NJGS) purchased a Robertson Geologging Ltd. heat-pulse flow meter (HPFM) in August 2002 to measure water flow in wells as part of a research study on the physical properties of fractured-bedrock aquifers. Research funding was provided from the NJ Department of Environmental Protection Hazardous Waste Spill Fund, administered by the Division of Science, Research and Technology. The HPFM is a geophysical sonde that measures water-flow rates that lie below threshold limits of conventional impeller devices. HPFM technology was developed in the early 1970's and is in widespread use today. This article summarizes its design and the accuracy of flow measurements using the instrument based on field tests conducted by the NJGS. It is important to understand the limitations of the instrument because it serves a vital role in establishing rates of ground-water flow and yield in bedrock aquifer studies. Quantitative measurements of interval yield are used in building a hydrogeological framework for various water-resource projects. This article examines some statistical relationships between controlled and measured fluid velocities in small-diameter wells based on standard operating procedures at velocities below 8 feet per minute (ft/min). Statistical differences between controlled and measured rates were calculated using Microsoft Excel software. Mathematical functions are derived for converting HPFM arrival (response) times into fluid-velocity values using the foot-per-minute measure. Mention of trade, brand, or company names is for identification purposes only and does not constitute endorsement by the NJGS.

DESIGN AND USE

The HPFM sonde contains a horizontal wire-grid heating element and thermistors located above and below it (fig. 1a). Apertures in the device permit the free flow of well fluid through the assembly (fig. 1b). Pulses of electric current are applied to the heating grid under surface command, warming the fluid in the vicinity of the grid. The warm-fluid front migrates towards the thermistors where it is detected. Because the spacing between the grid and both thermistors is fixed at 5 centimeters, the fluid velocity can be determined. Response time in seconds and calculated fluid velocity in feet per minute (ft/min) are measured at the surface by the logging technician using the RG Winlogger Software (Version 1). Complete product specifications are available from the Internet World-Wide-Web address http://www.geologging.com/english/products/probes/heat_pulseflowmeter.htm.

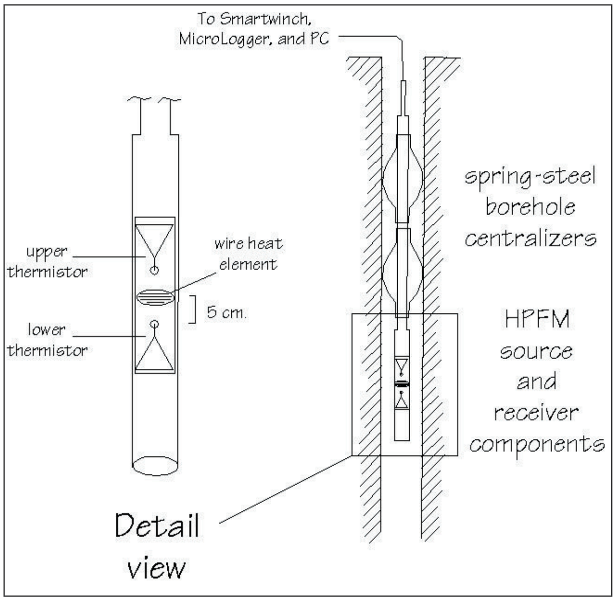

Figure 1a. Profile view of the heat-pulse meter (HPFM) in a borehole

Figure 1b. Photographs of the HPFM before deployment in a well. The HPFM is resting against the tripod/pulley assembly in the bottom photograph. The photo on the upper left shows the heating grid in the tool aperture. The top right photo shows the upper thermistor in the tool aperture.

Figure 2. The HPFM response time and fluid velocity (speed) measurements were made using Robertson Geologging RG Winlogger (Version 1) software. The data-acquisition interface shows a graph of the HPFM response time in seconds (x-axis) and the temperature differential (y-axis) of simultaneous temperature readings taken by the upper and lower thermistors expressed as the difference in counts per second (CPS). Both axes can be scaled using the pull-down menu boxes on the upper right part of the display. The direction of curve deflection indicates whether flow is upward, as shown above, or downward.

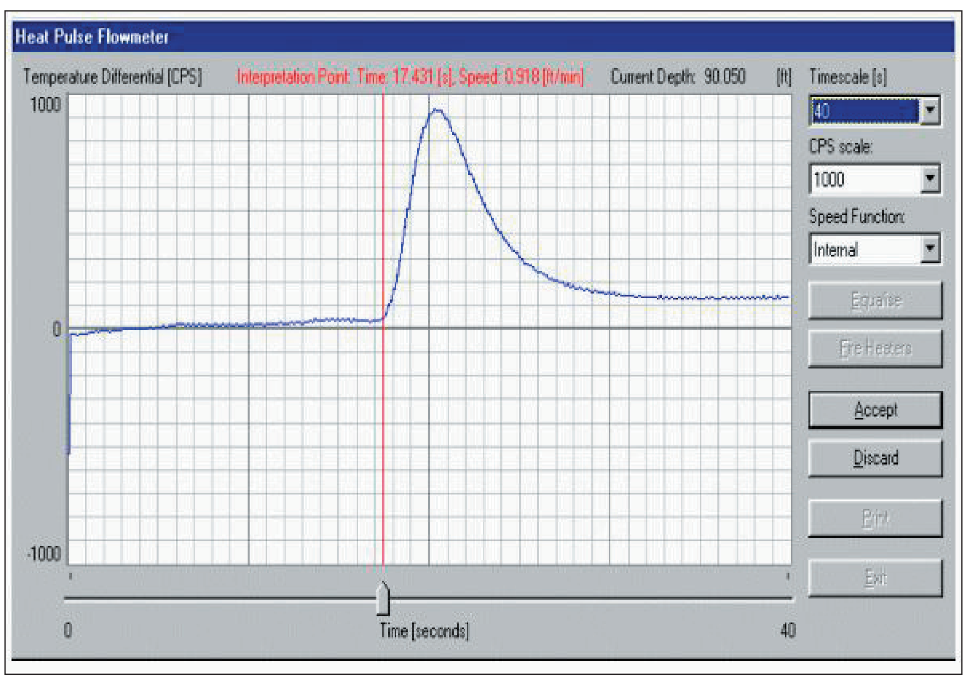

TABLE 1. Results of HPFM Tests 1 and 2 (4-inch well casing and variable flow rates from 0.5 to 17.0 ft/min)

Test	Q4[1] (gpm)	V4[2] (ft/min)	HPFMt[3] (sec)	HPFMv[4] (ft/min)	Vcalc4[5] (ft/min)	HPFMv[6] (pct)	Vcalc4[7] (pct)
1	11.000	16.923	0.266	7.190	18.008	-57.5	6.4
1	10.000	15.385	0.266	7.190	18.008	-53.3	17.1
1	9.050	13.923	0.418	6.515	12.568	-53.2	-9.7
1	8.000	12.308	0.418	6.515	12.568	-47.1	2.1
1	7.130	10.969	0.456	6.384	11.721	-41.8	6.9
1	6.800	10.462	0.569	6.050	9.810	-42.2	-6.2
1	6.090	9.369	0.722	5.692	8.107	-39.2	-13.5
1	5.000	7.692	0.802	5.535	7.456	-28.0	-3.1
1	4.150	6.385	1.147	4.998	5.601	-21.7	-12.3
1	3.110	4.785	1.453	4.643	4.636	-3.0	-3.1
1	2.070	3.185	2.325	3.937	3.182	23.6	-0.1
1	1.260	1.938	3.985	3.128	2.068	61.4	6.7
1	1.035	1.592	5.377	2.740	1.627	72.1	2.2
1	1.000	1.538	5.582	2.622	1.579	70.4	2.7
2	0.901	1.386	6.576	2.396	1.385	72.9	-0.1
1	0.865	1.331	5.615	2.613	1.572	96.4	18.1
2	0.792	1.218	8.160	2.070	1.166	70.0	-4.3
2	0.655	1.008	9.334	1.867	1.047	85.2	3.8
2	0.545	0.838	13.090	1.360	0.799	62.3	-4.7
2	0.391	0.602	17.604	0.912	0.630	51.5	4.7
2	0.364	0.560	19.948	0.714	0.570	27.5	1.8
2	0.000	0.000	32.250	0.000	0.388		
					Average	±51.4	±5.9

[1]Pump-discharge-volume rate (gallons per minute)
[2]Control velocity based on fixed pump-discharge-volume rate (Q4 / ~ 0.65 gal/ft).
[3]Heat-pulse flow meter response time.
[4]Heat-pulse flow meter fluid velocity (HPFMv).
[5]Adjusted fluid velocity incorporating the power-function correction to HPFMt.
[6]Percentage difference between the HPFMv and the control velocity.
[7]Percentage difference between the calculated velocity and the control velocity.

It is necessary to first allow the instrument to equilibrate in temperature with borehole fluids for a few minutes after it is positioned in the fluid column with the cable and winch. The lower the flow rate the longer the equilibration period needed. The thermistors are equalized before firing a heat pulse. Equalization and firing-control buttons are located in the right margin of the control-and-display window (fig. 2). The equalization process measures the difference in ambient heat at each thermistor in a short interval of time (~30 seconds) to establish a normalized baseline curve in heat-unit counts per second. The sonde log is displayed with time on the x-axis and the counts-per-second differential on the y-axis (fig. 2). The response curve is generated when the released pulse of heat passes by the thermistor. Depending on the direction of flow, either the upper or lower thermistor detects the warm-fluid front first. The time of arrival of the heat pulse is determined by sliding a cursor line in the software to a position on the display to the first inflection of the response curve. The time of arrival and calculated fluid velocity (speed) are displayed on the header bar of the control-and-display window (fig. 2). The lowest threshold value for measurable fluid velocity is 0.097 ft/min at 29.965 seconds. The highest value is 11.426 ft/min at 0.017 second. Time responses can be recorded up to 100 seconds and calculated fluid-velocity responses registered within a 30-second window. This window is considered by the manufacturer as the minimum time that a unit heat pulse will be transmitted upward under otherwise static flow conditions in the water column. The operating range of the instrument reported in the manufacturer's documentation is 0.1 to 3.0 meters per minute (0.30 to 9.84 ft/min).

The HPFM is repeatedly equalized and fired at a specific depth until reproducible or consistent results are obtained. Multiple values of travel-time and fluid velocity are measured and recorded at each depth, then combined later to determine an average time and speed for each set of measurements (table 1).

FIELD TESTS

A series of tests was run in three water wells of 4-inch or 6-inch diameter to assess the accuracy of HPFM measurements for travel times (HPFMt) and fluid velocities (HPFMv) obtained using the RG Winlogger software. The first two tests measure velocities in the cased part of a 4-inch well while pumping and discharging from the top of the well at stepped, controlled pumping rates over short periods of time. The well is constructed with 4-inch, schedule-40, polyvinyl chloride (PVC) pipe and is open to a single water-bearing interval below the casing. For the first test, the HPFM was lowered into the well to about 30 feet below land surface, about 28 feet below the 2-foot static-water level. A ½-horsepower submersible pump was next lowered into a position above the HPFM (fig. 3) about ten feet below the static water level to account for drawdown to the pumping level. The pump was connected in series to a flexible ¾-inch black-plastic pipe, a brass gate valve attached to the end of the plastic pipe to throttle flow, and an in-line GPI electronic digital turbine meter for measuring the rate of discharge. Control velocities ranged from 1.3 ft/min to 16.9 ft/min in 15 rate steps (table 1). The GPI meter has a reported accuracy of ± 1.5 percent at these flow rates. About 10 minutes was allotted between sets of measurements at each flow rate to stabilize the water level before taking HPFM readings. Multiple HPFM readings were taken at each pumping rate (table 1) and charted on a x-y scatter plot (table 1 and fig. 4a).

The second test utilized a Grundfos M1 submersible pump and Redi-Flow variable-speed control unit for flow velocities ranging from 0.5 to 1.4 ft/min. For this test, the HPFM was lowered to about 20 feet below the 2-foot static-water level. The Grudfos pump was attached to a garden hose and lowered about 10 feet below the water table. Fluid velocities were calculated from timed, volumetric discharges from the garden hose into a calibrated 2.0-liter Erlenmeyer flask. Steady-state velocities below 0.5 ft/min were not attainable using the Grudfos system. Multiple HPFM readings were obtained and charted together with the results from the first test (table 1, figures 4a and 4b).

Scatter plots of heat-pulse arrival times (HPFMt) versus control velocity (V4) and flow velocities recorded by the RG Winlogger software (HPFMv) were fit with linear and polynomial regression lines. Regression lines were used to approximate real-time and rate-variable data trends and yield a statistical measure of the deviation of two comparable sets of measurements. Logarithmic, exponential and power regression functions were examined for the various data sets. The deviation of trends was analyzed using the standard statistical measure r-squared (R^2). R^2 is determined using standard deviation and covariance operations:

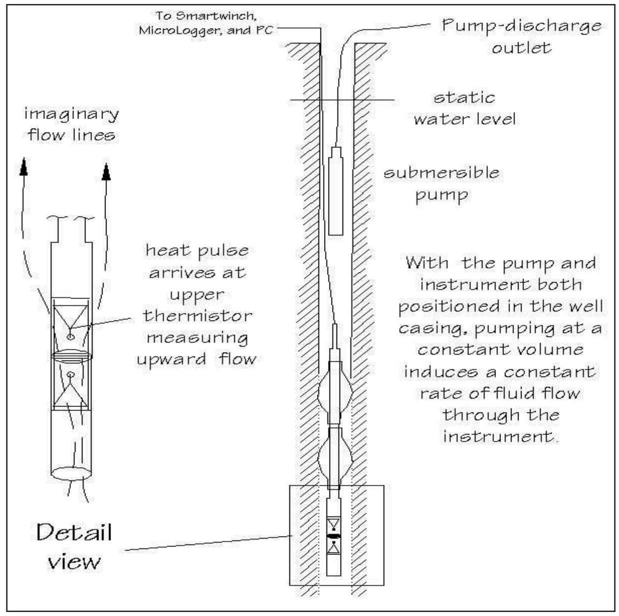

Figure 3. Profile view of the heat-pulse flow meter (HPFM) and a submersible water pump in a well casing showing stylized ground-water flow lines in detail. The HPFM and pump were set at fixed positions in well casings for tests 1 and 2 while pumping at stepped, variable flow rates. For tests 3 and 4, the HPFM was set at different positions in the open borehole while pumping at a fixed rate for determining interval fluid velocities.

$R^2 = r(X,Y) = [Cov(X,Y)] / [StdDev(X) \times StdDev(Y)]$ (eq. 1)

where X and Y are two data sets, Cov is the covariance of the data sets, and StdDev is the standard deviation of the two data sets. The value of R^2 approaches 100 percent (R^2=1.00) for a perfect correlation.

The standard deviation of each set of values was determined using:

$$StdDev = [1/n * (X_i - X_{ave})2]^{½} \quad \text{(eq. 2)}$$

where n is the number of measurements in set X, X_i is each measurement in the set, and X_{ave} is the arithmetic average of all X values. The superscript ½ denotes a square-root operation.

The covariance of the two trends is a statistical measure of the distance a value is likely to lie from its average value. Covariance is determined using:

$$Cov(X,Y) = [1/n * (X_i - X_{ave}) * (Y_i - Y_{ave})] \quad \text{(eq. 3)}$$

where X_i and Y_i are individual measurement in each set respectively, and X^{ave} and Y^{ave} are the arithmetic average of all values in each set.

Figure 4a shows that the RG Winlogger software calculates fluid velocities based on response times using a

TABLE 2a. Results of HPFM Test 3 (6-inch well and a constant flow rate of 7.71 ft/min)

Depth[1] (ft)	HPFMt[2] (sec)	HPFMs[3] (ft/min)	Vcalc4[4] (ft/min)	HPFMs[5] (percent)	Vcalc4[6] (percent)
45.00	1.07	5.11	5.93	-34	-23
55.95	0.99	5.21	6.28		
102.00	0.98	5.24	6.37		
116.00	1.01	5.19	6.20		
130.10	1.01	5.19	6.20		
150.00	1.79	4.33	3.92		
164.05	2.83	3.64	2.72		

TABLE 2b. Results of HPFM Test 4 (6-inch well and a constant flow rate of 7.71 ft/min)

Depth[1] (ft)	HPFMt[2] (sec)	HPFMs[3] (ft/min)	Vcalc4[4] (ft/min)	HPFMs[5] (percent)	Vcalc4[6] (percent)
47.95	0.87	5.478	6.99	-29	-9
76.05	0.92	5.379	6.68		
95.90	1.02	5.214	6.15		
120.00	1.05	5.175	6.01		
135.45	1.34	4.810	4.95		
148.30	1.58	4.559	4.33		
153.90	1.74	4.414	4.01		
170.00	1.88	4.301	3.78		
184.05	5.18	2.579	1.68		
188.30	12.05	1.478	0.85		

[1]Depth below ground surface of HPFM reading.
[2]Heat-pulse flow meter response time.
[3]Heat-pulse flow meter fluid velocity readout.
[4]Fluid velocity calculated using power function derived from 4-inch well test (eq. 5).
[5]Percent difference between the calculated velocity and the control velocity determined using the RG Winlogger software.
[6]Percent difference between the calculated velocity and the control velocity determined using the power function.

logarithmic function:

$y = -1.50 \, Ln(x) + 5.20$, $R^2=1.00$ where y is HPFMv and x is HPFMt. (eq. 4)

Figure 4a also shows a power function that most accurately defines the relationship between response times and control velocities:

$y \sim 6.25x^{-0.800}$, $R^2=0.99$ (eq. 5)

where y is the control velocity (V4) and x is the observed response time response (HPFMt).

A comparison of the two curves in figure 4a shows that the time-to-velocity conversion function programmed into the RG Winlogger software reports excessively high velocities above 4.5 ft/min (~1.5 sec. response time) and excessively low velocities below this value (table 1). A 4.50 ft/min velocity corresponds to about 2.9 gpm in a 4-inch well (4.5 ft/min * 0.65 gal/ft) and 6.6 gpm in a 6-inch well (4.5 ft/min * 1.47 gal/ft).

Although equation 5 best describes the instrument response times throughout the full range of tested velocities, flow values near the lower limit of precision of the instrument are best represented by a different logarithmic relationship (fig. 4b):

$y \sim -0.85Ln(x) + 3.00$, $R^2=0.98$ (eq. 6)

where y is the control velocity (V4) and x is the observed response time (HPFMt). Figure 4b also shows that both logarithmic functions (eqs. 4 and 6) have a lower limit for measuring flow at about 32 seconds response time, whereas application of the power function limits measurable flow to above 0.4 ft/min (~1/2 gpm in a 6-inch well).

Two other tests in two 6-inch domestic wells open to multiple water-bearing intervals assessed the accuracy of the instrument response time based on a fixed rate of discharge from the top of the well. These tests involved

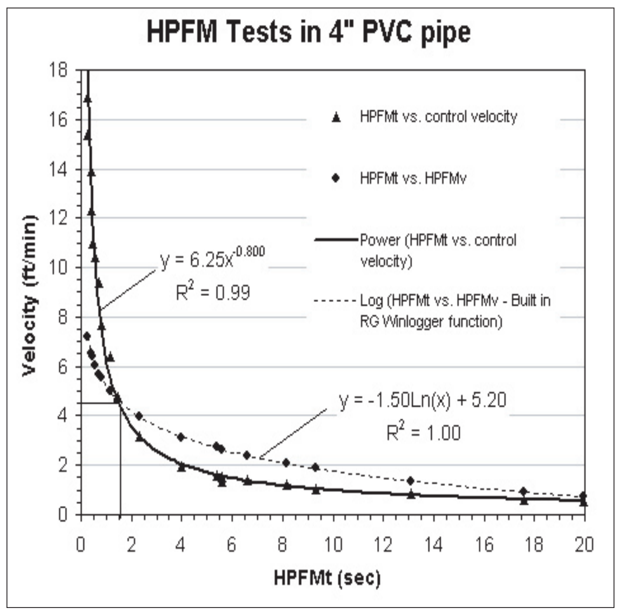

Figure 4a. Two mathematical relationships are charted for HPFM Tests 1 and 2 based on fixed, upward-directed flow rates between 0.5 ft/min and 18.0 ft/min in a 4-inch PVC pipe. The dashed trend line charts the logarithmic function used by RG Winlogger software to convert heat-pulse response times (HPFMt) to fluid velocities (HPFMv). The solid trend line charts the power function derived from tests 1 and 2 that accurately defines the relationship between HPFMt for the total range of flow velocities. A comparison of the two curves shows that they cross at about 1.6-sec. response time. This indicates that the RG Winlogger software reports excessively high velocities below 4.5 ft/min and excessively low velocities above 4.5 ft/min.

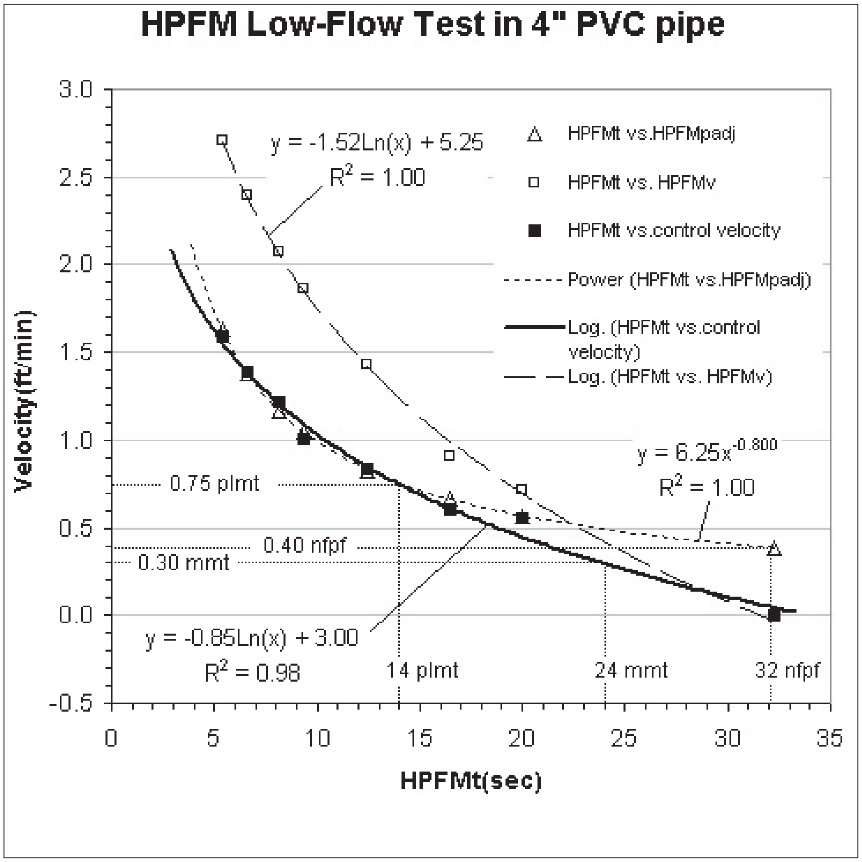

Figure 4b. Time and velocity relationships under low-flow rates from 0.0 to 3.0 ft/min. The long-dashed trend-line and corresponding logarithmic function is used with the RG Winlogger software and shows that the built-in function overmeasures fluid velocity in the low-flow range. The solid trend line corresponds to a logarithmic function that more accurately portrays heat-pulse response times for low-velocity, upward flows in a 4-inch PVC pipe. The short-dashed curve is the trend line based on the power function shown in figure 4a. The power relationship limits measurable flow to above 0.4 ft/min, based on a no-flow response time of about 32.0 seconds (nfpf, no-flow power function). Therefore, the logarithmic function defined by the solid trend line is a better measure of fluid velocities with low-flow response times exceeding 14 seconds (plmt, power-logarithm measurement threshold). The manufacturer's lower threshold of instrument precision is reported to be ~0.3 ft/min (mmt, manufacturers minimum threshold).

pumping from the casing near the top of the well at a constant rate and measuring interval flow velocities in both the open and cased parts of each well. Both wells were constructed with about 50 feet of 6-inch steel casing and have open intervals from the bottom of casing to less than 200 feet below the land surface in fractured Triassic-Jurassic red mudstone and siltstone of the Brunswick aquifer (Herman, 2001). Both wells have sustained yields exceeding the maximum rate of discharge of the pump used for the tests. Their specific capacities are 3.78 and 2.83 gpm per foot, respectively. Each open interval intercepts multiple water bearing zones (fig 5). Inspection of fluid temperature and electrical conductivity, borehole video and televiewer logs indicate that the vertical distribution and spacing of these water-bearing zones is similar to those elsewhere in the Brunswick aquifer (Michalski and Britton, 1997; Carlton and others, 1999; and Lewis-Brown and dePaul, 2000). These tests used the ½-horsepower submersible pump, gate valve, and in-line flow meter specified above. Static-water levels were about 2 feet to 10 feet below land surface, respectively. Both tests used a fixed discharge rate of 11.33 gpm (~ 7.71 ft/min for a 6-inch well) and the pump was positioned in the steel casing about 15 feet below the water table. The HPFM was positioned below the pump at multiple depths in the open hole of each well (table 2a and 2b). The pump ran for about ½ hour in each to stabilize the water table before HPFM measurements taken. The HPFM was repeatedly fired at each depth, and the resulting average response times were charted (tables 2a and 2b) to obtain a summary of the borehole flow-velocity profiles (fig 5). Tables 2a and 2b show that flow rates measured in casing in each well differ from the set values by as much as 29 to 34 percent. However, applying the time-to-velocity power function derived in Test 1 (eq. 5) to the observed response times reduces the observed error to a range of about -9 to -23 percent respectively.

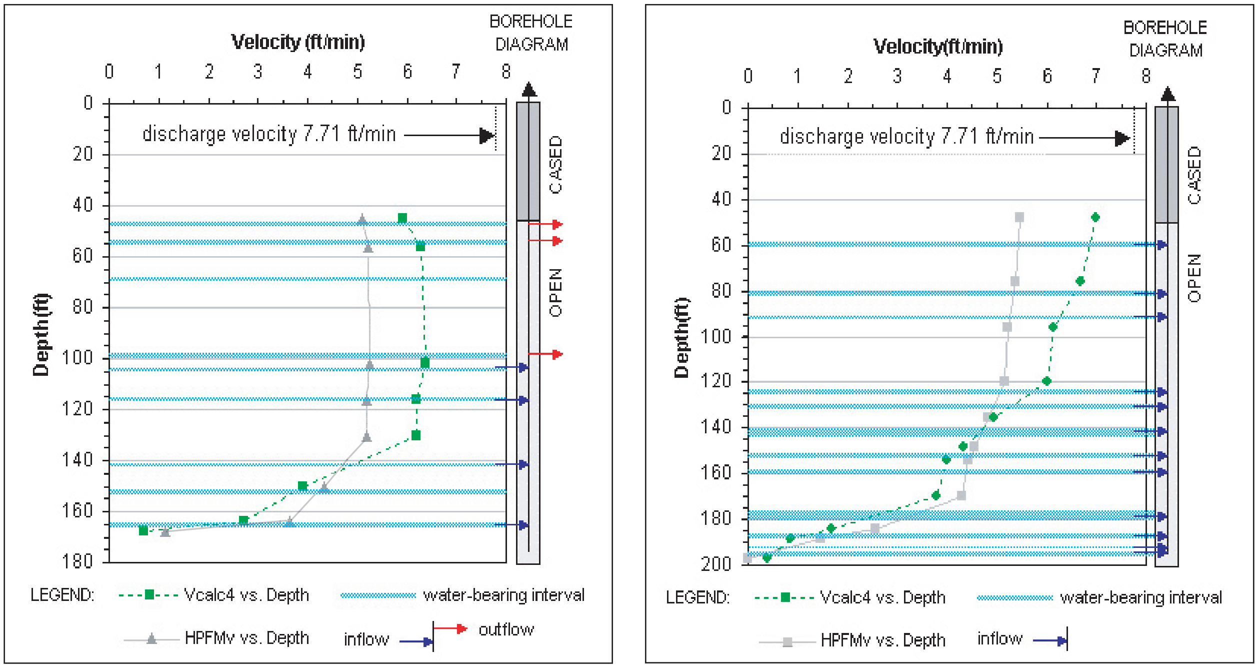

Figure 5. Calculated flow profiles and diagrams of two 6-inch domestic wells showing interval flow velocities derived from Tests 3 and 4 in conjunction with stratigraphic water-bearing intervals interpreted from borehole imaging systems and standard geophysical logs. The charted trend lines are flow profiles that vary as a function of the method used for determining interval velocities. Solid trend lines correspond to fluid velocities calculated from heat-pulse response times by the Winlogger software. Dashed trend lines correspond to adjusted velocities resulting from applying the power function derived in Test 1 and 2 for the 4-well tests (eq. 5). The adjusted velocities are about 10 percent to 20 percent more accurate with respect to the controlled flow rate than those calculated by use of the software (tables 1a and 1b).

DISCUSSION

Based on the tests outlined above, the Robertson Geologging HPFM is on average about 50 percent accurate for determining upward-directed fluid flow at velocities ranging from 0.5 to 17.0 ft/min in a 4-inch pipe, utilizing the time-to-velocity conversion function built into the RG Winlogger software. However the accuracy improves to more than 90 percent with application of time-to-velocity conversion functions derived from flow tests 1 and 2. The derived power function (eq. 5) should be used for calculating fluid velocities from response times of less than 14 seconds whereas the derived logarithmic function (eq. 6) should be used for calculating velocities from response times of more than 14 seconds. Heat-pulse arrival times exceeding 32 seconds should be viewed as no measurable flow. Fluid velocities calculated from response times below the manufacturer's reported threshold value of 0.3 ft/min (~24 sec, fig. 4b) should be viewed as qualitative because low-flow rates below 0.5 ft/min were not tested here.

The results of tests 3 and 4 show that in determining interval flow velocities in 6-inch wells open to multiple water bearing intervals, reliance on the time-to-velocity conversion function built into the RG Winlogger software produces an accuracy of the HPFM of about -29 to -34 percent. The accuracy of measurement improves to about -9 to -23 percent using the power function derived from tests 1 and 2. However, all calculated fluid-velocity measurements for the 6-inch wells are low with respect to the control velocities. These differences probably stem from variable flow conditions inside open holes of inconsistent diameter and local variations in water-instrument interaction.

Interval flow velocities measured with HPFM are combined with subsurface geological data including rock cores and geophysical logs, to develop hydrogeological profiles of aquifer intervals tapped by wells (Paillet, 1996). Mathematical methods for calculating the transmissivity of the uncased well interval can be used in conjunction with HPFM interval velocities to determine multiple, specific transmissive zones (Bradbury and Rothschild, 1985; Johnson and others, 2002). The interval-flow velocities reported here are applied to specific water-bearing intervals in a multilayered fractured-bedrock-aquifer framework. The location of water-bearing intervals is based on borehole geophysics including optical televiewer, caliper, fluid temperature, and fluid resistivity and conductivity logs. It is important to note that more accurate, quantitative values of transmissivity and interval flows can be obtained using brine-tracing methods (Michalski and Klepp, 1990) or by injection and pumping tests using straddle packers for discretely isolated zones (Shapiro and Hsieh, 1998).

In summary, the use of a HPFM can provide valuable information to help delineate the hydrogeological framework of aquifers penetrated by wells having partially uncased inetrvals. Interval flow velocities derived from HPFM studies should be interpreted with due regard to the specific test conditions under which the data were gathered. For example, rates of flow in different water-bearing intervals in any well can differ under nonpumping and pumping conditions and can be affected by fluctuations in the local water table from temporal recharge and discharge events. More testing of the HPFM is needed to measure controlled versus actual flow responses under downward-flow conditions, because the bulk of the HPFM assembly differentially obstructs currents flowing in opposite directions. More testing is also needed in 6-inch and 8-inch wells under test conditions similar to those used here for the 4-inch well in order to better understand the limitations of HPFM measurements made in wells of different diameters.

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