Field Test of the In Situ Permeable Ground Water Flow Sensor

by Andrew S. Alden and Clyde L. Munster

Abstract

Two in situ permeable flow sensors, recently developed at Sandia National Laboratories, were field tested at the Brazos River Hydrologic Field Site near College Station, Texas. The flow sensors use a thermal perturbation technique to quantify the magnitude and direction of ground water flow in three dimensions. Two aquifer pumping tests lasting eight and 13 days were used to field test the flow sensors. Components of ground water flow as determined from piezometer gradient measurements were compared with ground water flow components derived from the 3-D flow sensors. The changes in velocity magnitude and direction of ground water flow induced by the pump were evaluated using flow sensor data and piezometric analyses. Flow sensor performance closely matched piezometric analysis results. Ground water flow direction (azimuth), as measured by the flow sensors and derived in the piezometric analysis, predicted the position of the pumping well accurately. Ground water flow velocities measured by the flow sensors compared well to velocities derived in the piezometric analysis. A significant delay in flow sensor response to relatively rapid changes in ground water flow was observed. Preliminary tests indicate that the in situ permeable flow sensor provides accurate and timely information on the velocity magnitude and direction of ground water flow.

Introduction

Various in situ and well casing ground water flow sensors have been developed to monitor ground water flow. Portable in situ ground water flow meters were successfully used to evaluate shallow ground water flow around lakes during septic leachate surveys in Michigan and Minnesota (Kerfoot 1979; Kerfoot and Skinner 1981). Heat pulse probes for fully penetrating slotted wells designed for ground water flow measurement in two and three dimensions were developed by Kerfoot (1982). Ground water flow measurements using a two-dimensional heat pulse probe in monitoring wells at landfill sites were validated by subsequent investigations and long-term monitoring (Guthrie 1986). However, Melville et al. (1985) tested a two-dimensional heat pulse ground water flow meter under controlled laboratory conditions and found that small channelization between the slotted well casing and the probe could invalidate the flow meter response. Kerfoot (1988) provided recommendations for monitoring well construction and a new calibration procedure to increase the accuracy of heat pulse ground water flow meters.

The In Situ Permeable Flow Sensor

The flow sensor is 0.76 m long, 50 mm in diameter, and is permanently installed in saturated, porous, unconsolidated media at the point where ground water flow is to be determined. The flow sensor contains a resistance heater that

continuously heats the aquifer and an array of 30 thermistors located along the probe to measure temperature variations induced by ground water flow. Once the probe has been installed and calibrated, the velocity magnitude and direction of ground water flow, in three dimensions, is measured using a thermal perturbation technique. Analysis of raw temperature data using the proprietary software FLOW© allows near real-time measurement of a Darcy velocity vector. Ground water flow components are measured in a volume of approximately one cubic meter surrounding the probe. Measurement of ground water flow rates from 1×10^{-3} to 1 m/day are possible. Accuracy of direction measurement is estimated at $\pm 10°$ (Ballard 1996; Ballard et al. 1994; Ballard et al. 1996).

Previous Work

In 1994, a pump test was used to evaluate the effectiveness of the flow sensor at the Savannah River Site. Flow sensors were able to measure ground water flow velocities as low as 8.64×10^{-3} m/day with direction (azimuth) uncertainty values of $\pm 7°$ to $\pm 30°$. Values of measurement uncertainty were highly dependent upon pumping rate (Ballard 1994; Ballard et al. 1996).

In 1995, a flow sensor was used to assess the hydraulic characteristics at an underground oil storage facility in Weeks Island, Louisiana. The development of a sinkhole in the sandy sediments above a salt dome was an indication of possible intrusion of saltwater into the oil storage facility. A flow sensor was installed in a sand-filled fissure in the top of the dome at a depth of 76 m. Information gathered during a 17-day period indicated that probable contamination of the repository was occurring as water flowed downward through the crevice into the salt dome (Ballard and Gibson 1995).

In tests conducted at the Brazos River Site, long-term flow sensor and piezometric data were used to derive local saturated hydraulic conductivities. Comparison of the calculated hydraulic conductivities to those found in pump and slug tests at the site was used as a basis for evaluation of the velocity meter. Saturated hydraulic conductivities of 28.9 and 16.5 m/day were derived at depths of 13.7 and 18.3 m, respectively (Alden and Munster 1997).

Flow Sensor Tests

Test Overview

Flow sensor information and piezometric data from monitoring wells were collected during two aquifer pump tests at the Brazos River Research Site. The influence of pumping on ground water flow was determined using flow sensor output and piezometric data. The direction and magnitude of ground water flow obtained from the two independent flow sensors was compared to ground water flow components derived from a gradient analysis of piezometric data during the pump tests.

Test Site Description

The pump tests were performed at the Brazos River Hydrologic Field Site (Brazos River Site), which is located approximately 12 km west of College Station, Texas. The four-hectare site lies approximately 200 meters from the Brazos River, as shown in Figure 1. The alluvial aquifer at the site changes gradually from a fine sand at a depth of 8 meters to a coarse sand and gravel mixture at a depth of 21 meters. The aquifer is overlain by a surface layer of ships clay (very fine, mixed, thermic chromic hapluderts) that extends to a depth of 8 meters and is underlain by an impervious Yegua shale formation at 21 meters (Wrobleski 1996). Water levels in the aquifer typically fluctuate between 9 and 10 meters below the surface. Two pump tests were conducted using the site pumping well (Munster et al. 1996). The saturated hydraulic conductivity was determined at 20 site monitoring wells. In addition, slug tests were performed on 14 monitoring wells at the research site (Alden 1996). The pump and slug tests yielded a range of saturated hydraulic conductivity values from 3.4 to 83 m/day. Testing at the site suggests that saturated hydraulic conductivity values do not necessarily increase with depth. This may be attributed to the existence of clay lenses and other discontinuities often found in fluvial aquifers. Direct interaction between river stage and aquifer level has been observed (Alden and Munster 1997).
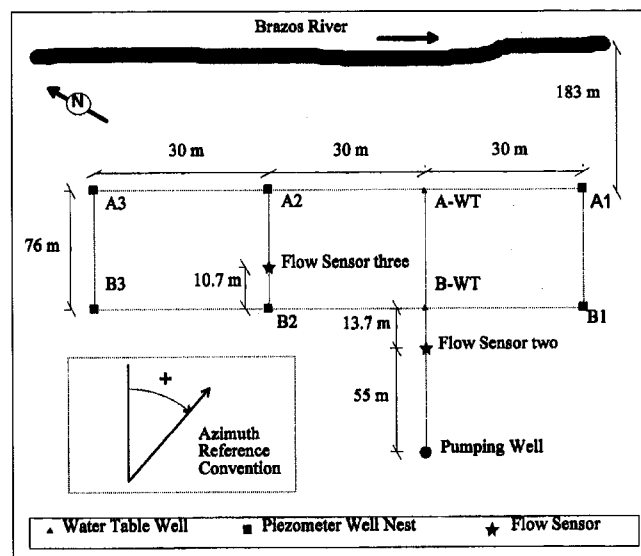

Figure 1. Plan view of the research site with the location of the piezometer well nests, water table wells, pumping well, and flow sensors (not to scale). A diagram of the ground water flow direction convention is also shown.

Instrumentation at the site includes 36 partially screened piezometric wells, four fully screened "water table" wells, two 3-D ground water flow sensors, and an 0.20-m-diameter pumping well, as shown in Figure 1 (Munster et al. 1996). The piezometric monitoring wells are arranged in a rectangular grid of well nests that is oriented parallel and perpendicular to the river (Figure 1). Each well nest contains four monitoring wells with short 150-mm-long polyvinyl chloride (PVC) wire-
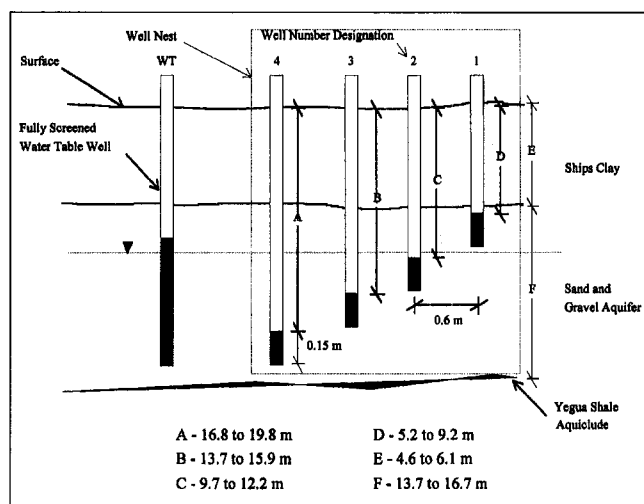
Figure 2. Elevation view of a typical well nest and water table well with soil stratigraphy and range of piezometer well screen depths shown (not to scale).
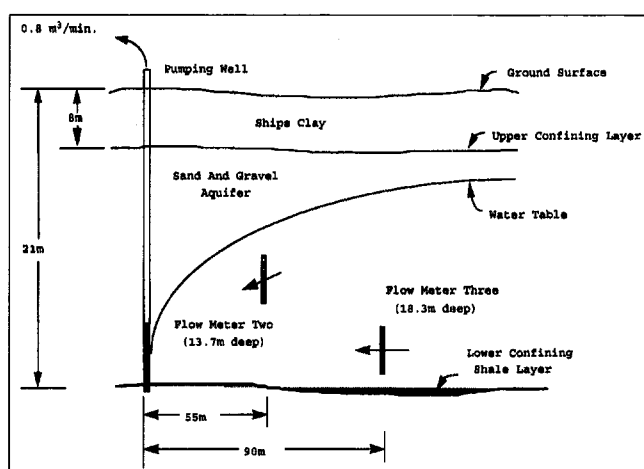
A - 16.8 to 19.8 m   D - 5.2 to 9.2 m
B - 13.7 to 15.9 m   E - 4.6 to 6.1 m
C - 9.7 to 12.2 m   F - 13.7 to 16.7 m

Figure 3. Elevation view of the pumping well and 3-D flow sensors at the Brazos River Site with soil stratigraphy also shown (not to scale).
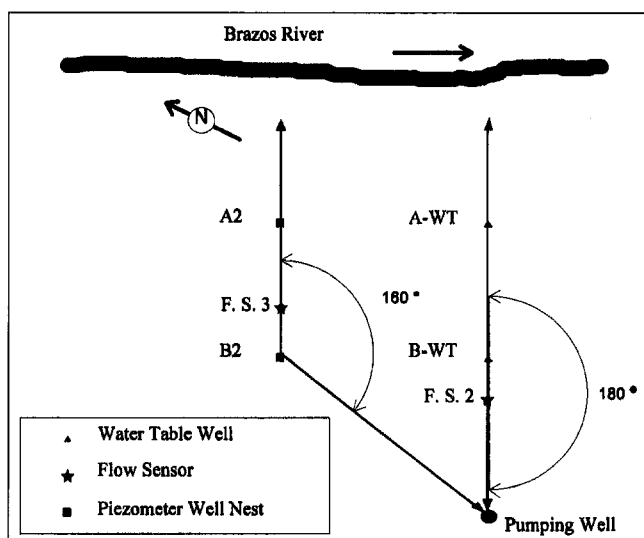

Figure 4. Diagram showing the geometric relationship between flow sensors two and three and the pumping well (not to scale). The true azimuth for the pumping well with respect to flow sensor three is 160° and to flow sensor two is 180° as shown.

wound (0.152-mm openings) well screens, which act as piezometers (Figure 2), that are numbered from one to four. The number one well is the shallowest and the number four well is the deepest. A typical well nest has screens located at 9, 12, 15, and 18 meters below the surface. The four "water table" wells are screened throughout the thickness of the aquifer with 0.254-mm slotted openings. Three water table wells lie within the main wellfield grid and one has been installed at the river to monitor river stage. All monitoring wells are 50.8-mm-diameter flush-threaded polyvinyl chloride (PVC). Water levels within all of the wells were continuously monitored and recorded in a system of four independent data collection systems (Munster et al. 1996).

Flow sensors were installed at the B-WT well and well nest B-2 at depths of 13.7 and 18.3 meters, respectively, as shown in Figures 1 and 3. Placement of the flow sensors was influenced by factors such as instrumentation access, distance from the pumping well, and proximity to the piezometers used in the gradient analysis. The geometric relationship between flow sensors two and three and the pumping well is shown in Figures 3 and 4.

Test Description

Two pump tests were used to evaluate flow sensor performance. The first pump test was conducted for eight days from Day 35 to Day 43, 1995. The second pump test was conducted for 13 days from Day 92 to Day 105, 1995. Flow sensor heaters and data acquisition equipment were activated three days prior to pumping to allow for temperature stabilization of the probe and surrounding aquifer. Water levels in the piezometer well system were measured manually prior to pumping to initialize the well data collection system. During the pump tests, a constant flow rate of approximately 0.8 m^3/min. was monitored by an in-line flow meter. All water from the pump test was transported off site to a nearby irrigation ditch using irrigation pipe. Immediately prior to the end of the pump test, all piezometric data was downloaded and well water levels were measured manually to reinitialize the well data collection system for aquifer recovery. Flow sensor and piezometric data collection intervals ranged from one minute at the start of the test to 360 minutes at the end of the test.

Methods of Analysis

Piezometric Data

Water level data from the monitoring wells was used to determine horizontal and vertical gradients at various levels within the aquifer. The piezometers analyzed were chosen based on horizontal and vertical proximity to the applicable velocity meter. The gradients between wells were used to calculate the direction and magnitude of ground water flow using Darcy's equation (Equation 1) and trigonometric analysis.

$$V = K_{sat} \times \frac{dH}{dL} \qquad (1)$$

Where:

V   = Darcy velocity (m/day)
K_{sat} = saturated hydraulic conductivity (m/day)
H   = total head (m)
L   = length (m)

In previous testing at the research site, saturated hydraulic conductivity values for each flow sensor installation location were determined through pump and slug tests. At flow sensor two, K_{sat} values ranged from 25.7 m/day (slug test) to 60.6 m/day (pump test). At flow sensor three, K_{sat} values ranged from 3.4 m/day (slug test) to 58.2 m/day (pump test) (Alden and Munster 1997). These K_{sat} values were used in the piezometric analysis to determine a range of ground water velocities for comparison to flow sensor results.

Piezometric Data at Flow Sensor Two

Piezometric wells in well nests A1, A2, B1, and B3 were used to calculate ground water gradient components at flow sensor two as shown in Figure 5. Piezometers A1-3 and A2-3 were used to find a gradient parallel to the river. The values for wells B1-3 and B2-3 were averaged to approximate water levels at flow sensor two. Values for A1-3 and A2-3 were also averaged and used in conjunction with the B1-3 / B2-3 average to derive a gradient perpendicular to the river (Equation 2):

$$G_{perp} = \left(\frac{B1\_3 + B\_32}{2} - \frac{A1\_3 + A2\_3}{2} \right) \div 1 \qquad (2)$$

Where:

G_{perp} = Hydraulic gradient perpendicular to the river at flow sensor three (m/m)
B1-3, B2-3, A1-3, A2-3 = Water levels in respective wells(m)
1 = distance between respective averaged points (m)

Piezometric Data at Flow Sensor Three

Piezometric wells in well nests A2, A3, B2, and B3 were used to find ground water gradient components at flow sensor three as shown in Figure 6. Wells B2-4 and A2-4 were used to determine a gradient perpendicular to the river. Wells A3-4 and A2-4 were used to find a gradient parallel to the river.

Flow Sensor Data

Raw temperature data from the flow sensor probe was used in FLOW to calculate the magnitude and direction of ground water flow for each velocity meter. Output from FLOW was transformed to yield the influence of pumping on the direction and magnitude of ground water flow. Options within FLOW allow for various data manipulations such as vector addition and
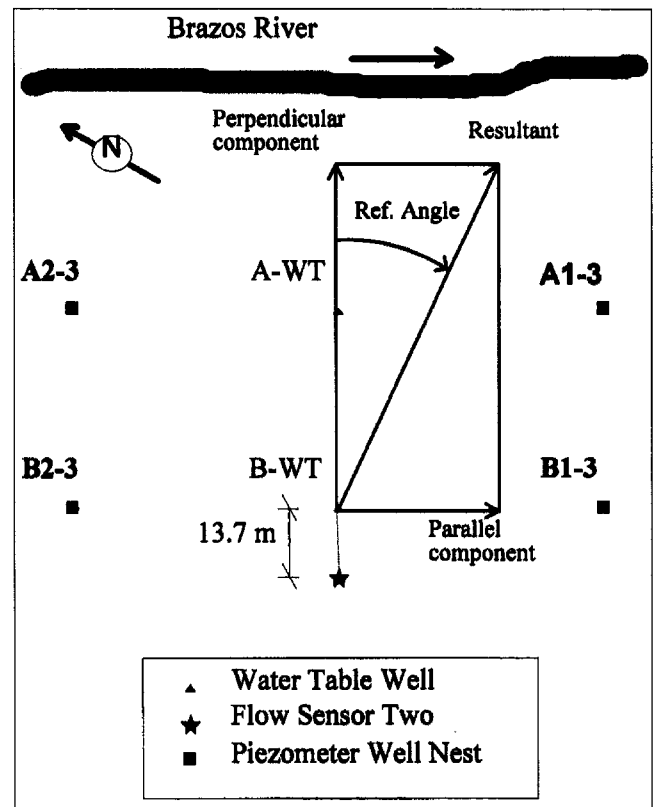
Figure 5. Plan view of the monitoring wells near flow sensor two (not to scale). Piezometric data from the bold-labeled wells was used to calculate ground water flow for comparison to flow sensor two output. The vector orientation convention is also shown.
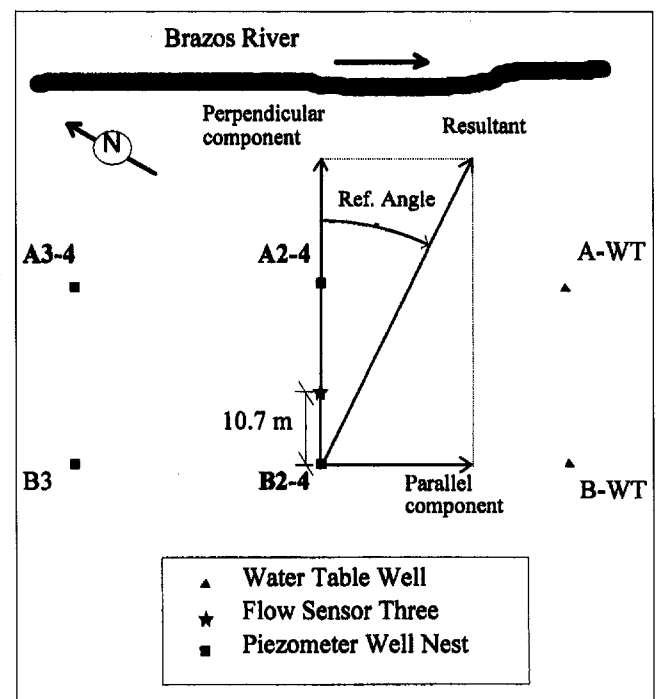

Figure 6. Plan view of the monitoring wells near flow sensor three (not to scale). Piezometric data from the bold-labeled wells was used to calculate ground water flow for comparison to flow sensor three output. The vector orientation convention is also shown.

data averaging (Ballard et al. 1994; Ballard 1996). Average ground water flow, as measured by the flow sensors immediately prior to pumping, was used as the background vector in the analysis of flow sensor data during the pump test.

Net Flow as a Basis of Comparison

A background ground water flow vector was derived at each flow sensor location using flow vectors found immediately prior to pumping. Manual well soundings were used as a basis for calculation of background ground water flows for use with the piezometric data. Respective background (prepumping) flow vectors were then subtracted from gross flow (during pumping) vectors to yield flow components due to pumping (net flow) as shown in Figure 7. The effects of river stage fluctuation are not considered in this analysis.

Net horizontal ground water velocities and azimuths are used as a basis of comparison between flow sensor and piezometric results. Net horizontal velocities from flow sensor results and piezometric analysis are compared to each other. Net azimuths from flow sensor results and piezometric analysis are compared to the known values of 180° for flow sensor two and 160° for flow sensor three as shown in Figure 4.

Results

The ground water flow components calculated from the flow sensor data and the gradient analysis of the piezometer wells are shown in Figures 8 through 11. Instability in the azimuth values at the beginning of each test are due to the extremely low initial net velocities. As pumping continues, the horizontal direction (azimuth) converges quickly to a final value. However,
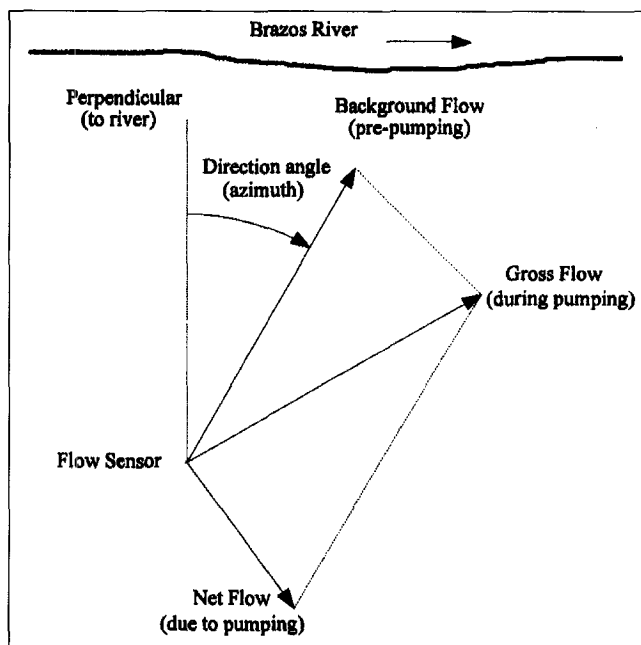

Figure 7. Plan view of the ground water flow vector subtraction convention used for derivation of net flow in the analysis of flow sensor and piezometric data. The direction (azimuth) convention is also shown.

the measured velocities converge to final values much more slowly as the aquifer is drawn down. Net vertical velocity values as measured by the flow sensors are shown in Figures 8 through 11 for informational purposes and were not used in evaluation of the flow sensors.

Pump Test One

Pump test one started at 11:40 a.m. of Day 35, 1995, and ended at 3:15 p.m. of Day 43, 1995. A power failure during the period from Day 38 to Day 41 resulted in the loss of data from both flow sensors. All data shown for the flow sensors during this period has been linearly interpolated. Flow sensor response to changes in ground water velocity at the beginning of each pump test is slower than that observed in the piezometric data. This occurred in all pump tests and may be due to the nature of the thermal phenomena that the flow sensor is dependent upon for its operation. Delays in flow sensor response to rapid changes in ground water velocity may result as heat is "flushed" from the 1 m³ volume around the velocity meter. The time of this delay is directly dependent upon the ground water velocity and may be considered as the "thermal time lag"; thermal time lag is defined here as the time required for ground water temperatures to stabilize in the vicinity of the flow sensor.

Flow Sensor Two

The ground water flow components for flow sensor two during the first pump test are shown in Figure 8. The azimuths of net horizontal flow as calculated by the flow sensor and piezometers converged quickly to 180° and 200°, respectively. The actual azimuth for the pumping well with respect to flow sensor two is 180° (Figure 4). The maximum net horizontal velocities using the saturated hydraulic conductivities from the slug tests (25.7 m/day) and the pump tests (60.6 m/day) were 0.04 and 0.1 m/day, respectively. The maximum net horizontal velocity measured by flow sensor two was 0.03 m/day. Vertical downward velocity increased from approximately zero to 0.01 m/day during initial pumping and then decreased to approximately 0.004 m/day in the latter portion of the test. The piezometric data displays a much faster reaction to aquifer pumping than does the flow sensor. The thermal lag time exhibited by the flow sensor is approximately two days.

Flow Sensor Three

The ground water flow components for flow sensor three during the first pump test are shown in Figure 9. The azimuths for net horizontal flow as calculated by the flow sensor and piezometers converge to 145° and 155°, respectively. The actual azimuth for the pumping well with respect to flow sensor three is 160° (Figure 4). The maximum net horizontal velocities using the saturated hydraulic conductivities from the slug tests (3.4 m/day) and the pump tests (58.2 m/day) were 0.020 and 0.220 m/day, respectively. Vertical downward velocity increased from approximately zero to 0.01 m/day at the

beginning of the pump test and remained at that level for the duration of pumping. The maximum net horizontal velocity measured by flow sensor two was 0.063 m/day. The flow sensor thermal lag is approximately two days.

Pump Test Two

Pump test two started at 4:30 p.m. of Day 92, 1995, and ended at 12:00 p.m. of Day 105, 1995. Again, a difference in velocity measurement response is evident at both flow sensors. Reversal of background ground water flow gradients was observed toward the latter part of the test period. A longer pumping period during pump test two and an increase in river stage resulted in reversal of ground water flow toward the river in the latter portions of the pump test.

Flow Sensor Two

The ground water flow components at flow sensor two during the second pump test are shown in Figure 10. The azimuths for net horizontal flow as calculated by the flow sensor and piezometers converged quickly

to approximately 175°. The actual azimuth for the pumping well with respect to flow sensor two is 180° (Figure 4). The maximum net horizontal velocities using the saturated hydraulic conductivities from the slug tests (25.7 m/day) and the pump tests (60.6 m/day) were 0.08 and 0.19 m/day, respectively. The maximum net horizontal velocity measured by flow sensor two was 0.068 m/day. Vertical flow was upward during the first half of the pump test and downward during the second half of the test at maximum velocities of approximately 0.01 m/day. The flow sensor thermal lag time is approximately two days.

Flow Sensor Three

The ground water flow components for flow sensor three during the second pump test are shown in Figure 11. The azimuths for net horizontal flow as calculated by the flow sensor and piezometers converged quickly to approximately 152° and 158°, respectively. The actual azimuth for the pumping well with respect to flow sensor three is 160° (Figure 4). The maximum net horizontal velocities using the saturated hydraulic conductivi-
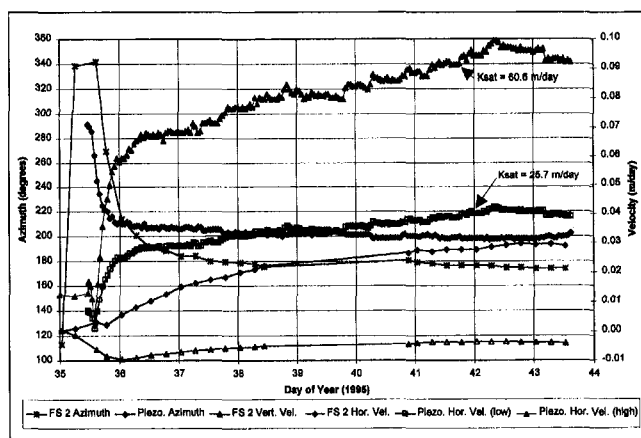

Figure 8. Net velocity magnitude and direction of ground water flow at flow sensor two during pump test one from piezometric and flow sensor data. The horizontal saturated hydraulic conductivity used in the piezometric analysis was 28.9 m/day. Negative vertical velocities indicate downward flow.
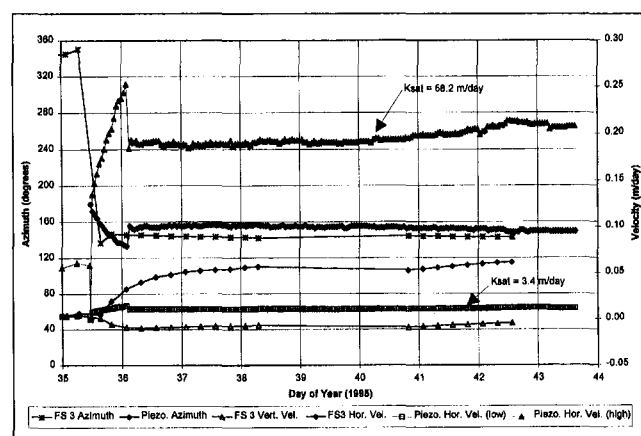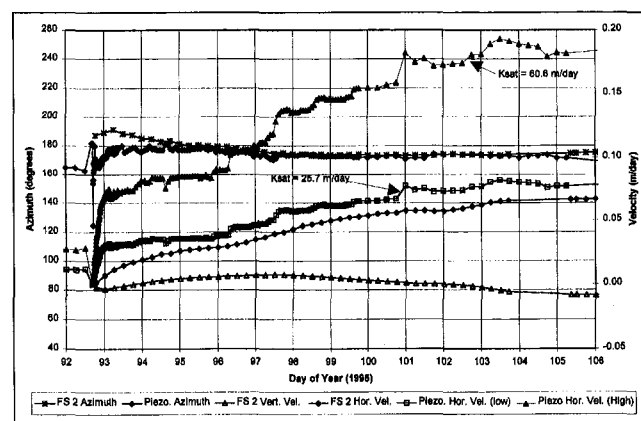

Figure 10. Net velocity magnitude and direction of ground water flow at flow sensor two during pump test two from piezometric and flow sensor data. The horizontal saturated hydraulic conductivity used in piezometric analysis was 28.9 m/day. Negative vertical velocities indicate downward flow.

Figure 9. Net velocity magnitude and direction of ground water flow at flow sensor three during pump test one from piezometric and flow sensor data. The horizontal saturated hydraulic conductivity used in the piezometric analysis was 16.5 m/day. Negative vertical velocities indicate downward flow.
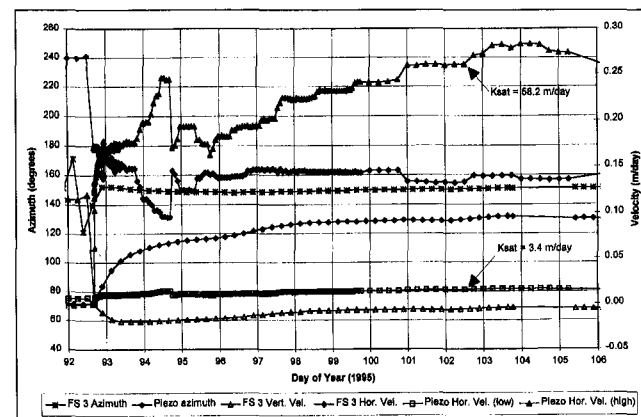

Figure 11. Net velocity magnitude and direction of ground water flow at flow sensor three during pump test two from piezometric and flow sensor data. The horizontal saturated hydraulic conductivity used in piezometric analysis was 16.5 m/day. Negative vertical velocities indicate downward flow.

Table 1
**Summary of Net Horizontal Ground Water Flow Components from Piezometric
and Flow Sensor Data for Pump Tests 1 and 2**

Location	Method	Pump Test 1			Pump Test 2		
		Azimuth (deg.)		Velocity	Azimuth (deg.)		Velocity
		Measured	Actual	(m/day)	Measured	Actual	(m/day)
FS 2	Flow Sensor	180	180	0.030	175	180	0.068
FS 2	Piezometer (K = 25.7 m/d)	200	180	0.040	175	180	0.080
FS 2	Piezometer (K = 60.6 m/d)	200	180	0.100	175	180	0.190
FS-3	Flow Sensor	145	160	0.063	152	160	0.095
FS 3	Piezometer (K = 3.4 m/d)	150	160	0.020	158	160	0.020
FS 3	Piezometer (K = 58.2 m/d)	150	160	0.220	158	160	0.270

Table 2
Summary of Flow Sensor Uncertainty Values from Pump Tests 1 and 2

Flow Sensor	Measurement	Pump Test 1			Pump Test 2		
		Low	High	Average	Low	High	Average
2	Horizontal Velocity (m/day)	0.04	0.04	0.04	0.03	0.05	0.04
2	Azimuth (degree)	5.00	9.50	7.40	6.10	11.00	9.60
3	Horizontal Velocity (m/day)	0.00*	0.03	0.02	0.03	0.04	0.04
3	Azimuth (degree)	0.00*	17.20	4.86	5.41	34.07	7.80

* Values shown as zero due to truncation of nonzero digits.

ties from the slug tests (3.4 m/day) and the pump tests (58.2 m/day) were 0.020 and 0.270 m/day, respectively. The maximum net horizontal velocity measured by flow sensor two was 0.095 m/day. Vertical downward velocity increased from near zero to 0.02 m/day during initial pumping and then decreased to approximately 0.008 m/day in the latter portion of the test.

Summary of Results

A summary of measured net ground water flow values from pump tests one and two is shown in Table 1. The velocity magnitude and direction of ground water flow shown in Table 1 are taken from discrete points in time where maximum measured velocities are observed. Table 2 shows values of uncertainty associated with the flow sensor data. Options within FLOW allow for the output of uncertainty data for each velocity and azimuth measurement. Uncertainty data is based on a Monte Carlo technique using a 95 percent confidence interval. Levels of measurement uncertainty generally decrease as ground water velocity increases (Ballard et al. 1994; Ballard 1996). Minimum, maximum, and average values of the uncertainty data associated with the pump tests are shown in Table 2.

Conclusions

The in situ permeable flow sensor is easy to use and relatively inexpensive. The velocity magnitude and direction of ground water flow are measured directly at a single point (one cubic meter) within the aquifer. Knowledge of hydraulic conductivity and aquifer

stratigraphy is not required and results are available immediately and continuously after installation, warm-up, and calibration are completed.

Flow vectors measured using piezometric and flow sensor data correlated well. The azimuths obtained from both methods predicted the approximate position of the pumping well at both flow sensor locations accurately. Ground water velocities measured by the flow sensors compared favorably to a range of velocities calculated in piezometric analyses using saturated hydraulic conductivity values from slug tests and pump tests. The flow sensor's dependence upon thermal phenomena in its operation may limit its application in situations where ground water velocities change rapidly. This is generally not the case in most ground water studies, but could occur where ground water flow is influenced by pumps or streams. Preliminary tests indicate the in situ permeable flow sensor to be a useful tool in determining the direction and magnitude of ground water flow in three dimensions.

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Biographical Sketches

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