

Assessment of River-Floodplain Interactions

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Andrew S. Alden, Project Engineer, K.W.Brown Environmental Services, College Station, TX 77845

Clyde L. Munster, Assistant Professor, Agricultural Engineering Department, Texas A&M University, College Station, TX 77843-2117

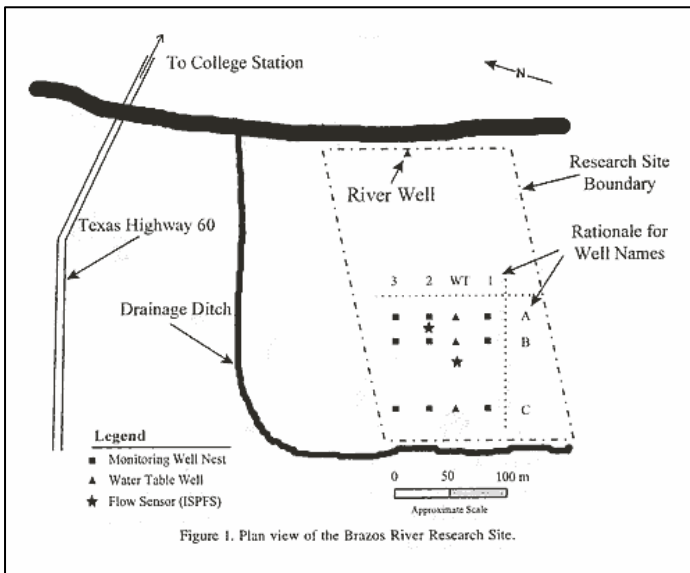
ABSTRACT

The interaction between the Brazos River and the adjacent floodplain aquifer was studied for 200 days in 1995 at a ground-water research site near College Station, Texas. Two In Situ Permeable Flow Sensors (ISPFS) and a grid of well nests were used to correlate river stage to the magnitude and direction of ground-water flow at depths of 13.7 m and 18.3 m in the unconfined alluvial aquifer. Linear relationships between ground-water flow and river stage were determined at each depth. The floodplain aquifer responded differently to changes in river stage at the 13.7 m and 18.3 m depths. The horizontal velocity, parallel and perpendicular to the river, decreased with increasing river stage and increased with decreasing river stage, at both depths. However, the rates of change varied between the two depths. This caused the magnitude and direction of ground-water flow to be different at the two depths. The upward vertical velocity increased with increasing river stage at the 13.7 m depth and decreased with increasing river stage at the 18.3 m depth. At the 13.7 m depth, vertical ground-water flow gradually changed from upward to downward flow with long term river stage decline. Downward ground-water flow was not observed at the 18.3 m depth. Assessment of river-aquifer interactions indicates that a direct and measurable relationship exists between river stage and ground-water flow components at the site. The magnitude and direction of groundwater flow in the alluvial floodplain aquifer may be predicted if river stage is known.

INTRODUCTION

Stream-Aquifer Interaction

Assessment of the interaction between ground water and surface water has become increasingly important as concern by regulatory agencies



for the quality and quantity of water supplies has increased (Texas Water Commission, 1989). The quantification of the hydrologic connection between a stream and the adjacent aquifer is also important to agricultural, industrial, and municipal interests as competition for diminishing water supplies escalates (Postal, 1989).

The hydrologic relationship between streams and aquifers is often complex, especially in transient systems where stream stage fluctuates or ground water is pumped from the aquifer. From pump tests conducted along the Miami River near Venice, Ohio, Walton and others (1967) concluded that streambed infiltration could be estimated and that streambed losses were constant and at a maximum rate after the aquifer water table was below the streambed. Sophocleous and others (1987), used pump tests along the Arkansas River in Kansas to assess surface-ground-water interactions. They observed drawdown in wells on the opposite side of the river and the aquifer responded as a leaky confined aquifer. Actual stream losses were less than analytical solutions predicted. Dunlap and others (1985) used well level and river stage data in a modeling study of ground-water surface-water interactions in the Arkansas River in Kearney and Finney Counties, Kansas. This section of the Arkansas River has received little or no ground-water discharge since 1923. River recharge to the aquifer was controlled by streambed permeability and the hydraulic gradient between the river and the aquifer water table.

Johnson and others (1989) used test holes and monitoring wells to assess surface-water/ground-water interactions along Cottonwood Creek in Shasta and Tehama Counties, California. Ground water flowed principally within the most permeable aquifer material and recharge from the stream occurred if a downward gradient existed. Ground-water gradients were upward and no recharge from the stream was indicated when the stream channel crossed silt and clay formations. A study on the Nashua River in north-central Massachusetts by de Lima (1991) used infiltration tests to establish that the vertical hydraulic conductivities of the streambed ranged from 0.6 to 1.5 m/day. Sophocleous (1991) determined that ground-water level rises in the Great Bend Prairie aquifer of Kansas was caused by flooding in adjacent rivers. Wolf and Helgesen (1993) calculated an average aquifer discharge of 0.8 m³/s along a 222 km segment of the Kansas River between Wamego and Topeka, Kansas using 40 yr of data. Greeman (1995) summarized 2,328 water level measurement by the U. S. Geological Survey from 1985-1992 in the Calumet aquifer and surface-water levels in Northern Lake County, Indiana. Water tables sloped toward the streams in the study area and ground-water gradients increased with decreasing river stage.

The establishment of connections between surface and ground water has also led to increased concern for water quality (Texas Water Commission, 1989). Field studies by Ragan (1968) and Sklash and Farvolden (1979) have shown rapid movement of contaminated ground water to nearby streams following rainfall events. In addition, contaminated surface water has the potential to degrade ground-water supplies. A study by Schultmeyer (1995) revealed that the water quality properties and constituents of the alluvial aquifer that served as a water supply for Cedar Rapids, Iowa, changed to follow the water

quality trends of the Cedar River due to drawdown. Wang and Squillane (1994) detected herbicide transport from the Cedar River to floodplain wells. up to 50 m from the river during high stream flow.

Field studies (Munster et al., 1996) and computer model simulations (Chakka and Munster, 1996) at the Brazos River ground-water research site have shown that river stage determines water levels in the floodplain aquifer. Infiltration from rainfall events has been shown to have little or no effect on ground-water levels. Rainfall events influence water levels primarily by increasing river stage through surface runoff. At the Brazos River research site, the floodplain aquifer typically discharges to the river. However, during high river stages, the aquifer is recharged by the river.

Research Objectives

The research objectives were to: a) assess ground-water/surface water interactions at two depths in the Brazos River floodplain aquifer and b) develop predictive relationships that would correlate ground-water flow; to river stage at these two depths.

FIELD METHODS

The interaction between the Brazos River and the floodplain aquifer was evaluated at a ground-water research site located approximately 12 km west of College Station, Texas (Munster et al., 1996). The 8.5 hectare research site is located on a typical section of the lower Brazos River floodplain and is 183 m from the river (Figure 1). The unconfined, heterogeneous, alluvial aquifer is overlain by a Ships clay layer that is, on average, 7.3 m thick as shown in Figure 2. The site is underlain by an impermeable Yegua shale formation at a depth of 20.1 m (Cronin and Wilson, 1967). The aquifer gradually changes from a fine sand at a depth of 7.3 m to a coarse sand and gravel mixture at a depth of 20.1 m. Water levels in the aquifer typically fluctuate between 9 m and 10 m (elevations = 58.5 m and 57.5 m) below the surface. Slug and pump tests at the research site have yielded saturated hydraulic conductivity (K_{sat} values that ranged from 3.2 ~ to 150 m/day (Wroblewski, 1996). A comprehensive characterization of the Brazos River research site is included in Munster and others (1996).

Instrumentation at the site includes 36 partially screened piezometric wells, four 'water table' wells, two In Situ Permeable Flow Sensors (ISPFS), and an 0.2 m diameter pumping well. The piezometric monitoring wells are arranged in a three-by-three grid of well nests that is oriented parallel and perpendicular to the river (Figure 1). Each well nest contains four monitoring wells with 150 mm long, polyvinyl chloride (PVC), wire-wound well screens with 0.15 mm openings (Figure 2). Wells in each nest are numbered one through four. Well one is the shallowest and well four is the deepest. The well nest screens were located, on average, at depths of 7.3, 11.0, 14.5, and 18.4 m below the surface (Figure 2). The four 'water table' wells have 0.25 mm slotted openings and are screened throughout the thickness of the aquifer. Three 'water table' wells lie within the main well field grid and a fourth 'water table' well was installed at the river to monitor river stage (Figure 1). All monitoring well casings are 51 mm diameter, flush

threaded, PVC. Water levels in all of the wells were continuously monitored and recorded in a system of four, independent data collection systems (Munster et al., 1996).

The In Situ Permeable Flow Sensor

Two ISPFSs (two and three) were installed and functioned properly during field testing conducted in 1995 (Alden and Munster, 1997). ISPFS two was installed near the B- WT water table well at a depth of 13.7 m (elevation = 53.8 m; Figure 3). ISPFS three was installed near the B-2 well nest at a depth of 18.3 m (elevation = 49.2 m; Figure 3). The placement of the ISPFSs was influenced by factors such as instrumentation access and proximity to the piezometers, which were used for gradient analysis comparison.

The ISPFS measures ground-water flow using a thermal perturbation technique (Ballard, 1996) and is permanently installed in saturated, porous, unconsolidated media at the point where ground-water flow is to be determined. This is typically accomplished through use of the hollow stem auger drilling process. Natural backfill must collapse around the probe as the augers are removed to insure intimate contact between the aquifer formation and probe. This is typically accomplished through reverse rotation of the auger as it is pulled from the bottom of the borehole. A 25 mm diameter PVC conduit is connected to the device and extends to the surface to protect power and data wiring. ISPFS orientation is accomplished through alignment of the data wiring conduit with a known azimuth.

A resistance heater within the 0.76 m long, 50 mm diameter cylindrical sensor heats approximately one cubic meter of the surrounding aquifer. An array of 30 thermistors located below the surface of the sensor skin measures small variations in temperature that occur as a result of ground-water flow around the device. Post- manufacturing calibration of the sensor in an isothermal bath adjusts relative thermistor accuracy to approximately 0.01 °C. Computer analysis of temperature variations among the 30 thermistors using FLOW allows determination of a Darcy flow rate and direction in three dimensions. FLOW is a proprietary software program developed at Sandia National Laboratories for use with ISPFSs. Measurement of ground-water flow rates from 3×10^{-3} to 3×10^{-1} m/day at a resolution of 3×10^{-4} m/day are possible. Accuracy of direction measurement is estimated at $\pm 10^\circ$. Instrument accuracy is highly dependent upon the thermal properties of the aquifer and the magnitude of velocities being measured (Ballard, 1994).

Aboveground instrumentation for the ISPFS includes a power supply and data acquisition equipment. Power requirements for the probe depend upon aquifer characteristics and typically range from 60 to 120 watts. The data acquisition equipment used in this test was manufactured by Campbell Scientific Inc., and includes a CR-10 datalogger, an AM416 4x16 relay multiplexer, a data storage module, and a MD9 serial interface module. Comparable data acquisition equipment from other manufacturers can be used. After installation, the heater within the probe is activated to stabilize the temperature of the surrounding aquifer. Temperature data from 0.5 and 3.5 hours after initial heater start-up is used to produce a calibration file that adjusts

the raw temperature data for the thermal properties of the media surrounding the probe. This calibration file is used for all subsequent measurement with this probe installation. Once thermistor temperatures stabilize, measurement of ground-water flow can begin. The time and frequency of discrete ground-water measurements is determined by datalogger programming parameters and options in the FLOW software.

Data Collection

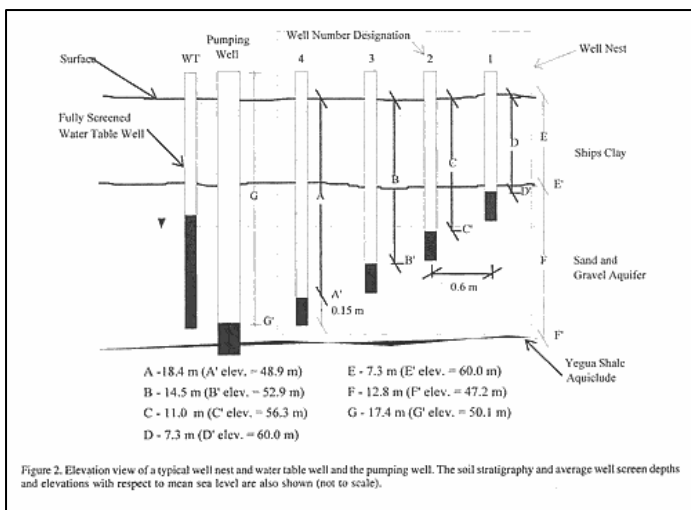
Data at the research site was collected from day 80 (March 21) to day 210 (July 29) of 1995. Water well levels, ISPFS data, and river stage were monitored. Water levels in the site wells were manually recorded on irregular intervals. ISPFS data was collected on six hour intervals and stored in two, independent and synchronized dataloggers. Power interruptions resulted in the loss of data during the days 132-148 and 150-156 at ISPFS three. A combination of power interruptions and support equipment failure resulted in the loss of data from days 149-210 at ISPFS two.

River stage was approximated by piezometric data taken from a water table well located on the river bank. River well levels were collected every hour by a datalogger. Equipment failures resulted in loss of data on days 102- 105, 111-115, 129-130,131-135, 144-157, 166-168, and 171-174. A pumping test was performed at the site from day 92 to 105 of 1995. A pumping rate of approximately 0.68 m³/min was maintained in the 0.2 m pumping well during that period.

METHODS OF ANALYSIS

Piezometric Data

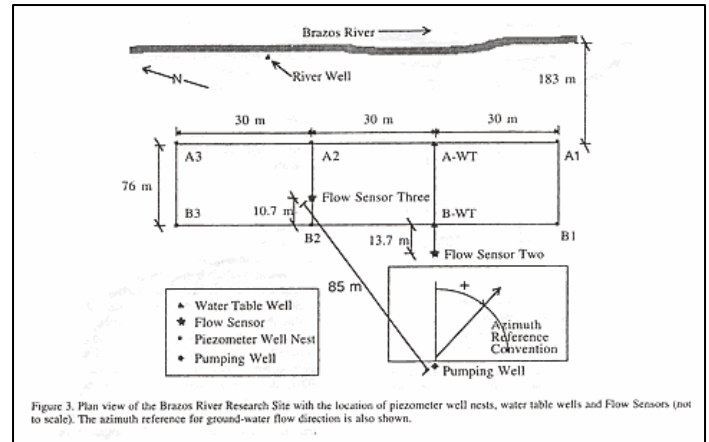
Water level data from the monitoring wells was used to determine horizontal and vertical gradients at two levels within the aquifer. These gradients were used to calculate the direction and magnitude of ground-water flow at each ISPFS location using Darcy's equation.



Piezometers used in the analysis were chosen based on close horizontal and vertical proximity to the applicable ISPFS. Averaging of piezometric data from multiple wells was performed where required to approximate water levels in the proximity of each ISPFS.

Piezometric Data at ISPFS Two

Piezometric wells in well nests A1, A2, B1, and B3 were used to calculate ground-water gradient components at ISPFS two as shown in Figure 4. The number three well in each well nest was chosen for the



analysis due to proximity (in depth) to ISPFS two which is located at a depth of 13.7 m. Water table wells A- WT and B- WT were not used in the analysis since they are fully screened. Piezometers A1-3 and A2-3 were used to find the gradient parallel to the river. Water levels in the B 1-3 and B2-3 wells were averaged to approximate a piezometric head at BW-T. Water levels from A1-3 and A2-3 were averaged to approximate a piezometric level at AW-T. The B 1-3/B2-3 average and A 1-31 A2-3 aver-age were used to calculate a gradient perpendicular to the river at ISPFS two as shown in Equation 1.

Where:

G_{perp} = Hydraulic gradient at ISPFS two perpendicular to the river (mlm);
 BI-3, B2-3, AI-3, A2-3 = Water levels in each well (m);
 L = distance between the A and B rows of wells (76 m).

A summary of calculated ground-water gradients, horizontal velocities, and flow directions with respect to the river stage is shown in Table I.

Piezometric Data at ISPFS Three

Piezometric wells in nests A2, A3, B2, and B3 were used to find ground-water gradient components at ISPFS three as shown in Figure 5. The number four well in each well nest was chosen for the analysis due to proximity (in depth) to ISPFS three. 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. An equipment malfunction resulted in the exclusion of well B3-4 from the analysis. A summary of calculated ground-water gradients, horizontal velocities, and flow directions for ISPFs two and three are shown with respect to the river stage in Tables 2 and 3, respectively.

Saturated Hydraulic Conductivity

Piezometric assessment of ground-water flow is based on the Darcy equation and is dependent upon a saturated hydraulic conductivity (K_{sat} value for velocity determination. A K_{sat} value is not required for determining ground-water flow from ISPFs data.

Average saturated hydraulic conductivities values for each ISPFs location were calculated from piezometric and ISPFs data. Horizontal ground-water gradients calculated from piezometric data and horizontal velocities measured by the ISPFs were used in the Darcy equation to calculate K_{sat} values (Tables 1 and 2) at discrete points in time.

The mean K_{sat} value at ISPFs two, at a depth of 13.7 m, was 28.9 m/day with a standard deviation of 1.01 m/day. The mean K_{sat} value at ISPFs three, at a depth of 18.3 m, was 16.5 m/day with a standard deviation of 2.13 m/day. These derived saturated hydraulic conductivities compare favorably to other hydraulic conductivities measured at the site using pump and slug tests (Table 3). The lower than expected values of K_{sat} at deeper aquifer depths in the gravel portion of the aquifer suggests that heterogeneities such as clay lenses may exist.

Reduction of the raw temperature data from the ISPFs was accomplished using the software program FLOW. Calibration files developed during laboratory isothermal calibration and initial field operation are applied in FLOW to convert raw temperature data to ground-water flow data.

Table 1. Summary of hydraulic gradients from the monitoring wells and horizontal ground-water velocities from the Flow Sensor used to calculate K_{sat} at Flow Sensor two. Negative velocities indicate flow away from the river or upstream. The corresponding river stage is also shown.

Day of Year 1995	River stage (m)	Hydraulic Gradient (m/m)			FS 2 Horiz. Vel. (m/day)	Calc. K_{sat} (m/day)
		Perpendicular	Parallel	Resultant		
92	54.6	0.0023	0.0005	0.0024	0.067	28.32
105	56.0	-0.0007	0.0007	0.0010		
123	54.6	0.0022	0.0005	0.0023	0.068	29.60
137	57.3	-0.0005	0.0015	0.0015	0.043	27.76
142	55.5	0.0016	0.0005	0.0017	0.050	29.85
157	55.3	0.0020	0.0007	0.0021		
166	56.5	0.0010	0.0010	0.0014		
174	55.0	0.0026	0.0005	0.0026		
193	54.0	0.0036	0.0004	0.0037		
206	53.8	0.0038	0.0004	0.0038		
						AVERAGE = 28.9

Table 2. Summary of hydraulic gradients and Flow Sensor horizontal ground-water velocities used to calculate K_{sat} at Flow Sensor three. Negative velocities indicate flow away from the river or upstream. The corresponding river stage is also shown.

Day of Year 1995	River Stage (m)	Hydraulic Gradient (m/m)			FS 3 Horiz. Vel. (m/day)	Calc. K_{sat} (m/day)
		Perpendicular	Parallel	Resultant		
88	54.7	0.0014	-0.0009	0.0017		
92	54.6	0.0020	-0.0001	0.0020	0.031	15.47
105	56.0	-0.0022	0.0011	0.0024		
123	54.6	0.0020	-0.0002	0.0021	0.037	18.04
137	57.3	-0.0006	0.0010	0.0012		
142	55.5	0.0016	-0.0002	0.0016		
157	55.3	0.0019	0.0001	0.0019	0.026	13.56
166	56.5	0.0008	0.0008	0.0011	0.022	19.36
174	55.0	0.0023	-0.0004	0.0024	0.043	18.42
193	54.0	0.0032	-0.0006	0.0033	0.052	15.66
206	53.8	0.0034	-0.0006	0.0035	0.05	14.91
						AVERAGE = 16.5

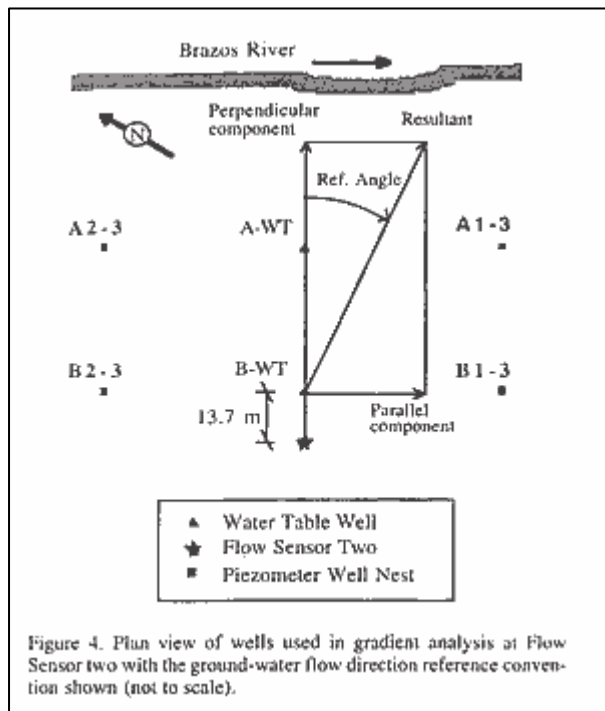
Table 3. Summary of K_{sat} values in the alluvial aquifer at the Brazos River site.

Location	Source	Average Depth (m)	Average K_{sat} (m/day)	Wells Used in Analysis
Flow Sensor Two	Flow Sensor	13.7	28.9	N.A.
	Pump Test ¹	14.9	60.6	B1-3, B2-3
	Slug Test ^{2,4}	14.9	19.0	B1-3, B2-3
	Slug Test ^{1,4}	14.9	32.3	B1-3, B2-3
Flow Sensor Three	Flow Sensor	18.3	16.5	N.A.
	Pump Test ¹	18.8	58.2	A2-4, B2-4
	Slug Test ^{2,4}	18.8	3.2	A2-4, B2-4
	Slug Test ^{1,4}	18.8	3.6	A2-4, B2-4

¹ (Wobleski, 1996)
² Bouwer and Rice analysis (Bouwer, 1989)
³ Hvorslev analysis (Hvorslev, 1951)
⁴ (Alden and Munster, 1997)

RESULTS

Surface-water/ground-water interactions were assessed by evaluating the changes in ground-water flow induced by river stage fluctuations. Changes in the velocity and direction of ground-water flow were determined at depths of 13.7 m and 18.3 m in the aquifer. Changes in horizontal ground-water velocities, perpendicular and parallel to the river, and vertical ground-water velocities were calculated using piezometric and ISPFs data. An evaluation of the surface-water/ground-water interactions resulted in the observance of linear relationships between changes in river stage and changes in the ground-water flow components.



ISPFs Data

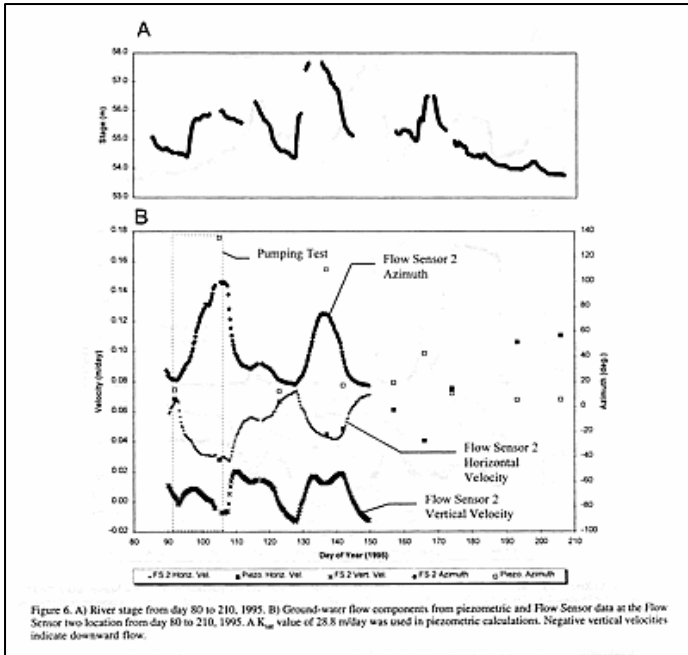


Figure 6. A) River stage from day 80 to 210, 1995. B) Ground-water flow components from piezometric and Flow Sensor data at the Flow Sensor two location from day 80 to 210, 1995. A K_{gw} value of 28.8 m/day was used in piezometric calculations. Negative vertical velocities indicate downward flow.

River-Aquifer Interaction

The ground-water flow components and river stage for days 8 to 208, 1995 at ISPFS locations two and three are shown in Figures 6 and 7, respectively. The flow components include horizontal ground-water velocity from piezometric and ISPFS data, vertical ground-water velocity from ISPFS data, and horizontal flow direction (azimuth) from piezometric and ISPFS data. Ground-water velocity and direction vary in response to gradient changes induced by river stage fluctuations. Large changes in ground-water velocity components and azimuth from day 92 to day 105 are due to pump tests conducted at the research site pumping well.

Horizontal ground-water velocities measured by piezometric and ISPFS methods compared very well as shown in Figures 6 and 7. At both depths (13.7 m and 18.3 m), the horizontal ground-water gradients and velocities were inversely related to river stage. Wolf and Helgesen (1993) reported that the ground-water flow to the Kansas River was slowed or even reversed due to increased water levels in the river. Similar trends were reported by Schulmeyer (1995) for the Cedar River in Iowa.

At the Brazos River research site, after the maximum river stage of 57.7 m on day 135, the horizontal velocity decreased to a minimum of 0.043 m/day at the 13.7m depth and 0.019 m/day at the 18.3m depth. After a low river stage (54.3 m) on day 127, the horizontal velocity increased to 0.074 m/day at the 13.7m depth and 0.044 m/day at the 18.3m depth.

At the 13.7 m depth (ISPFS 2), vertical velocities varied from +0.018 m/day (upward) at maximum river stage on day 135 to -0.015 m/day (downward) at low river stage on day 127. At the 18.3 m depth (ISPFS 3), vertical velocities varied from +0.005 m/day (upward) on day 135 and 0.00 m/day on day 127.

Piezometer and ISPFS measured azimuths sometimes varied, especially at high or low river stages. While there was good agreement between ISPFS and piezometric measurement of azimuths at the ISPFS three, location; measured azimuth values at the ISPFS two location vary by as much as 30°. At high river stage, ground-water flow was generally oriented in the down-stream direction, while at low river stage ground-water flow was generally oriented perpendicular to the river. This type of flow orientation was also observed by Hibbs (1996) on the Colorado River near Bastrop, Texas.

At the 13.7 m depth, the azimuth of horizontal ground-water flow varied from 75° (90° is parallel to the river) at the highest river stage on day 135 to 15° (0° is perpendicular to the river) at low river stage on day 127. At the 18.3 m depth, the azimuth varied from 135° on day 135 to -15° (flow oriented upstream) on day 127. Ground-water flow in the upstream direction was also observed in the piezometric data and may be caused by heterogeneities inherent in fluvial deposits.

Ground-water flow was affected at both ISPFS locations during the pumping test (days 92 to 105). As shown in Figure 3, ISPFSs two and three were located 55 m and 85 m from the pumping well, respectively. The well screen of the pumping well was located from 17.0 m to 21.6 m below the surface. Therefore ISPFS two was above the well screen at 13.7 m and ISPFS three was at the same level as the well screen at 18.3 m.

The direction of ground-water flow changed immediately at ISPFS three. The azimuth changed from -14.4° to 116° very rapidly (approximately 1 day), indicating a direct hydraulic connection between the aquifer at ISPFS three and the pumping well. The final azimuth at ISPFS three was 143° at the end of the pump test. At ISPFS two, the direction of ground-water flow changed gradually from 28.4° to 100.0° during the 13-day pump test.

At ISPFS three the horizontal ground-water velocity increased from 0.034 m/day to 0.063 m/day and the upward vertical velocity changed from 0.017 m/day to 0.014 m/day during the pumping test. The horizontal ground-water velocity at ISPFS two responded in the opposite direction as the velocity decreased from 0.06 m/day to 0.032 m/day during the pumping test. The vertical velocity at ISPFS two initially increased in the upward direction from 0.00 m/day to 0.09 m/day, then steadily decreased to a downward flow of -0.01 m/day by the end of the pump test.

The relationships between river stage and the ground-water flow components at each ISPFS location were evaluated (Figures 8 and 9). Parallel and perpendicular horizontal ground-water velocities were derived from piezometric data, and vertical ground-water velocities were from ISPFS data. Ground-water flow data from the pump test

period (day 92 to 105) was not used in the analysis. Linear regression equations were developed to permit horizontal ground-water velocities, parallel and perpendicular to the river, and vertical ground-water velocities, to be estimated from river stage. The direction of ground-water flow could then be calculated from the predicted horizontal and vertical ground-water velocities.

Similar responses to river stage changes were apparent in the perpendicular and parallel horizontal ground-water velocities at the 13.7m and 18.3m depths. For increasing river stage, the perpendicular velocity decreased and the parallel velocity increased. However, the horizontal velocity changes induced by river stage fluctuations at the 13.7m depth were much greater than those at the 18.3m depth. At the 13.7m depth, the perpendicular velocity varied from 0.11 m/day to -0.02 m/day; whereas, at the 18.3m depth, the perpendicular velocity varied from 0.06 m/day to -0.01 m/day.

Distinctly different responses to river stage were observed in the vertical ground-water velocities at each ISPFS location. At the 13.7m depth, increasing river stage increased the vertical upward velocity. At the 18.3m depth, increasing river stage decreased the vertical upward velocity. These different responses may be attributed to aquifer heterogeneities, such as clay lenses or high permeability zones, that resulted from fluvial deposition.

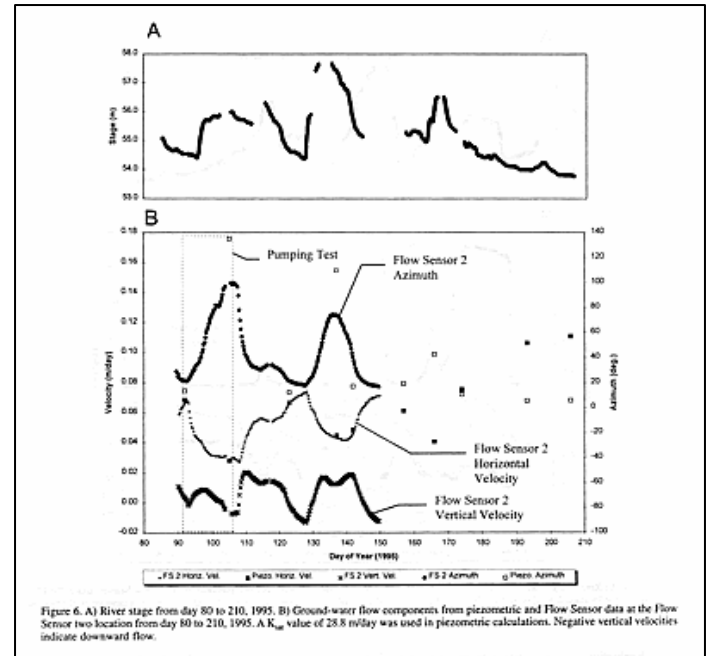
A reversal of vertical ground-water flow from upward to downward occurs when the river stage drops below 53.6 m at the 13.7 m depth and when the river stage rises above 57.4 m at the 18.3 m depth. River stages between 53 m to 58 m were recorded during the investigation and are typical near the Brazos River research site.

SUMMARY

The floodplain aquifer responded differently at the two depths to changes in river stage due to aquifer heterogeneity. The horizontal velocity (parallel and perpendicular), at both depths, decreased with increasing river stage and increased with decreasing river stage. However, the rates of change varied between the two depths, and consequently, the direction of ground-water flow was very seldom, if ever, in the same direction at the two depths.

In addition, the vertical velocity responded in opposite directions due to river stage fluctuations. At the 13.7 m depth, the vertical velocity increased upward with increasing river stage while at the 18.3 m depth, the upward vertical velocity decreased with increasing river stage. At the 13.7m depth, vertical ground-water flow was directly related to river stage fluctuations. As the river stage began to rise, vertical ground-water flow gradually changed from downward flow to upward flow. As the river stage began to decline, the vertical ground-water flow gradually changed from upward to downward flow. Reversal of vertical ground-water flow occurred at a river stage of approximately 53.6m.

At the 18.3m depth, the vertical ground-water velocity fluctuated very little in response to changes to river stage. The flow was always in an upward direction except at very low river stages where the vertical velocity approached zero. Calibration of piezometric data with ISPFS data J produced saturated hydraulic conductivities of 28.9 m/day and 16.5 m/day at depths of 13.7 m and 18.3 m, respectively.



CONCLUSIONS

Ground-water flow in aquifers is often idealized with flow in the same horizontal and vertical direction throughout the depth of the aquifer. However, in floodplain aquifers that are primarily influenced by fluctuations in the adjacent stream, the magnitude and direction of ground-water flow can vary significantly with depth. ISPFS and piezometric data were used to assess the interaction between the Brazos River and the floodplain aquifer at two depths, 13.7 m and 18.3 m.

Changes in the magnitude and direction of ground-water flow induced by river stage fluctuations and a pumping test were studied for 200 days in 1995. In general, the ISPFS values and piezometric values were in close agreement. Linear relationships between river stage and the magnitude and direction of horizontal and vertical ground-water flow in the floodplain aquifer were developed. In addition, saturated hydraulic conductivity (K_{sat} values at two depths in the aquifer were derived using piezometric and ISPFS data. These K_{sat} compared favorably to K_{sat} values determined from pump and slug tests performed at the research site.

Evaluation of river-aquifer interaction suggests that a direct and measurable connection exists between river stage and ground-water flow components. Derivation of linear regressions for each ground-

water flow component at depths of 13.7 m and 18.3 m, suggests that horizontal and vertical ground-water velocity and direction of horizontal ground-water flow may be predicted if river stage is known.

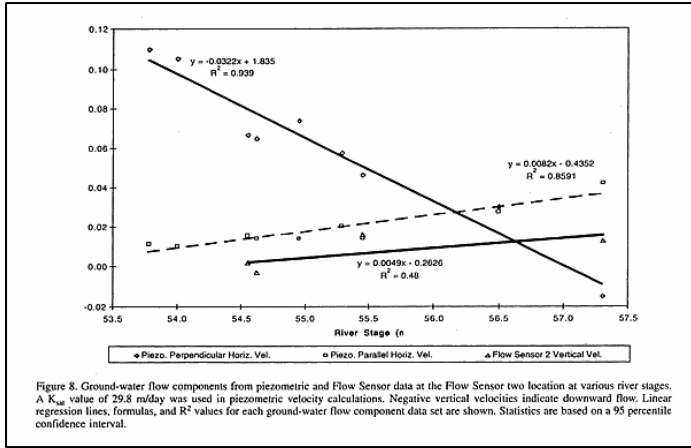


Figure 8. Ground-water flow components from piezometric and Flow Sensor data at the Flow Sensor two location at various river stages. A K_{gw} value of 29.8 m/day was used in piezometric velocity calculations. Negative vertical velocities indicate downward flow. Linear regression lines, formulas, and R^2 values for each ground-water flow component data set are shown. Statistics are based on a 95 percentile confidence interval.

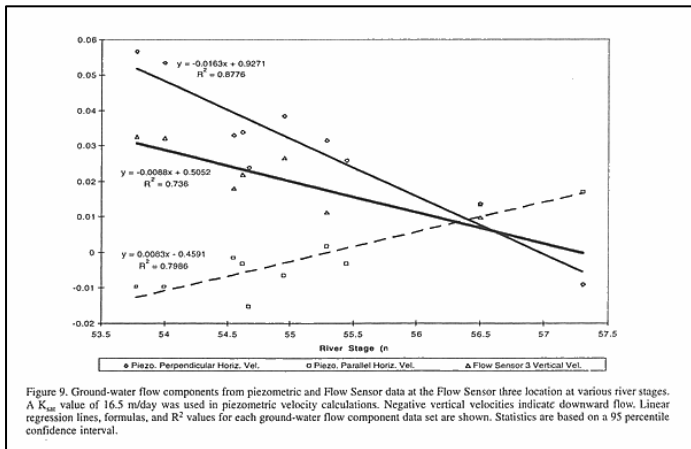


Figure 9. Ground-water flow components from piezometric and Flow Sensor data at the Flow Sensor three location at various river stages. A K_{gw} value of 16.5 m/day was used in piezometric velocity calculations. Negative vertical velocities indicate downward flow. Linear regression lines, formulas, and R^2 values for each ground-water flow component data set are shown. Statistics are based on a 95 percentile confidence interval.

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