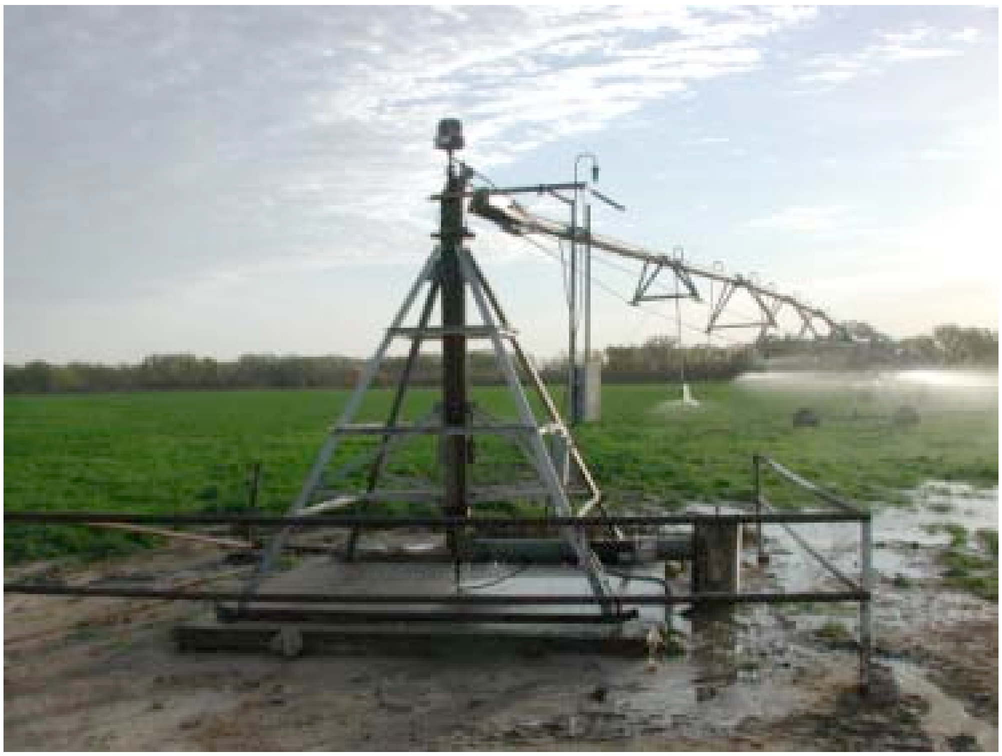
Kansas Geological Survey

ANALYSIS OF TWO PUMPING TESTS AT THE O'ROURKE BRIDGE SITE ON THE ARKANSAS RIVER IN PAWNEE COUNTY, KANSAS



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EXECUTIVE SUMMARY

Two multi-day pumping tests were performed by the Kansas Geological Survey at the O'Rourke Bridge site adjacent to the Arkansas River in Pawnee County, Kansas, near the city of Larned. The first test was performed in the alluvial aquifer of the Arkansas River over two days in September of 2002, while the second test was performed in the High Plains aquifer over four days in October of 2003. The major objectives of these tests were to obtain information about the hydraulic and geochemical responses of the aquifers to extended periods of pumping, the degree of hydraulic connection between the two aquifers, and the impact of pumping on streamflow in the Arkansas River. An extensive network of observations wells was installed for the two tests using direct-push electrical conductivity logging to delineate the stratigraphy and to select the intervals over which the wells were screened. Pumping-induced changes in water level (drawdown) were measured using both automatic and manual methods, and water samples were collected before, during, and after the pumping tests. Type curve analyses were performed on the drawdown data from two observation wells for each pumping test. The transmissivity and specific yield of the Arkansas River alluvial aquifer estimated from the first test were 3800 ft^2/d and 0.31, respectively. There was no indication of vertical flow from the underlying High Plains aquifer during the test, so no information about the hydraulic conductivity of the confining unit separating the two aquifers could be obtained. The transmissivity and storage coefficient of the High Plains aquifer estimated from the second test were 5400 ft^2/d and 1.7×10^{-4}, respectively. The pumping in the High Plains aquifer induced flow from the overlying alluvial aquifer, and the hydraulic conductivity of the confining unit separating the two aquifers was estimated to be 7.0×10^{-3} ft/d. The parameter estimates obtained from both tests are consistent with the geologic composition of the unconsolidated aquifers and confining unit.

The Arkansas River rarely flowed at the O'Rourke Bridge site during 2002 and 2003, so these pumping tests could not provide direct information about the impact of nearby pumping on the flow of the Arkansas River. Regardless, the chemistry data collected during the first test indicate that pumping of the alluvial aquifer will draw in water from the Arkansas River. The results of the

second test indicate that pumping of the High Plains aquifer will induce downward movement of water from the alluvial aquifer through the confining unit. Thus, pumping in the High Plains aquifer in the vicinity of the O'Rourke Bridge would also be expected to impact flow in the Arkansas River, but the timing and magnitude of that impact will be dramatically different from that for pumping from a well in the alluvial aquifer located close to the stream.

The details of the well construction for the pumping well used in the second test are not known. However, it appears that the gravel pack extends upward from the High Plains aquifer through the confining unit to the alluvial aquifer, a common design for irrigation wells installed prior to the last two decades. This design appears to have resulted in movement of water from the alluvial aquifer to the High Plains aquifer through the gravel pack prior, during, and after the pumping test. This flow through the gravel pack must always be considered when interpreting the results of analyses of water samples collected in the vicinity of older irrigation wells in the High Plains aquifer.

INTRODUCTION

Two multi-day pumping tests were performed by the Kansas Geological Survey (KGS) at the O'Rourke Bridge site adjacent to the Arkansas River in Pawnee County, Kansas, in September of 2002 and October of 2003. The September 2002 (henceforth, S2002) test was directed at increasing information about the hydraulic properties of the Arkansas River alluvial aquifer (henceforth, alluvial aquifer) and its relationship to the river. The October 2003 (henceforth, O2003) test was directed at increasing information about the hydraulic properties of both the High Plains aquifer and the confining unit that separates the High Plains and alluvial aquifers at the O'Rourke Bridge site. These tests were done as part of a multi-year research effort of the KGS focused on developing a better understanding of the nature of stream-aquifer interactions in the middle reaches of the Arkansas River, the impact of irrigation pumping on stream flow, and the role of phreatophytes in the hydrology of the riparian zones of Kansas rivers. The Division of Water Resources of the Kansas Department of Agriculture was the primary source of funding for this project. Some of the observation wells used for these tests were constructed with funds provided by the KGS and Groundwater Management District #5. Jim Butler of the Geohydrology Section of the KGS served as the principal investigator for the project.

REPORT OVERVIEW

The following report will be divided into three main sections: Preliminary Site Investigation, Pumping Test Procedures and Results, and Water Sampling and Analysis Procedures and Results. The first section provides a site overview and descriptions of the direct-push electrical conductivity profiling method used to select screened intervals for the observation wells and the direct-push approach used to install those wells. The second section consists of a description of the procedures used to perform and analyze the two pumping tests and an interpretation of the results. The third section consists of a description of the field procedures used for acquiring water samples for geochemical analyses and an interpretative discussion of the results of those analyses.

PRELIMINARY SITE INVESTIGATION

Site Overview

The location of the O'Rourke Bridge site is in Pawnee County, Kansas, just northeast of the city of Larned. Figure 1a shows the position of the site relative to the city of Larned and the channel of the Arkansas River, while Figure 1b shows the locations of the pumping and observation wells at the site. Well LEA2 was pumped for the S2002 test, while well IW was pumped for the O2003 test. Seven observation wells (LEA1, LEA4, LEA5, LS30, LWPH1, LWPH2, and LWPH3) were used in the S2002 test, while thirteen observation wells (PT1a, PT1b, PT2, PT3, PT4a, PT4b, PT5a, PT5b, PT6, PT7, LWC2, LEA5, and LEC2) were used in the O2003 test. Eleven of these wells were temporary observation wells installed specifically for this project, while eight were existing wells in the KGS monitoring network at the O'Rourke Bridge site. The KGS has been performing research on stream-aquifer interactions at this site since the summer of 2001.

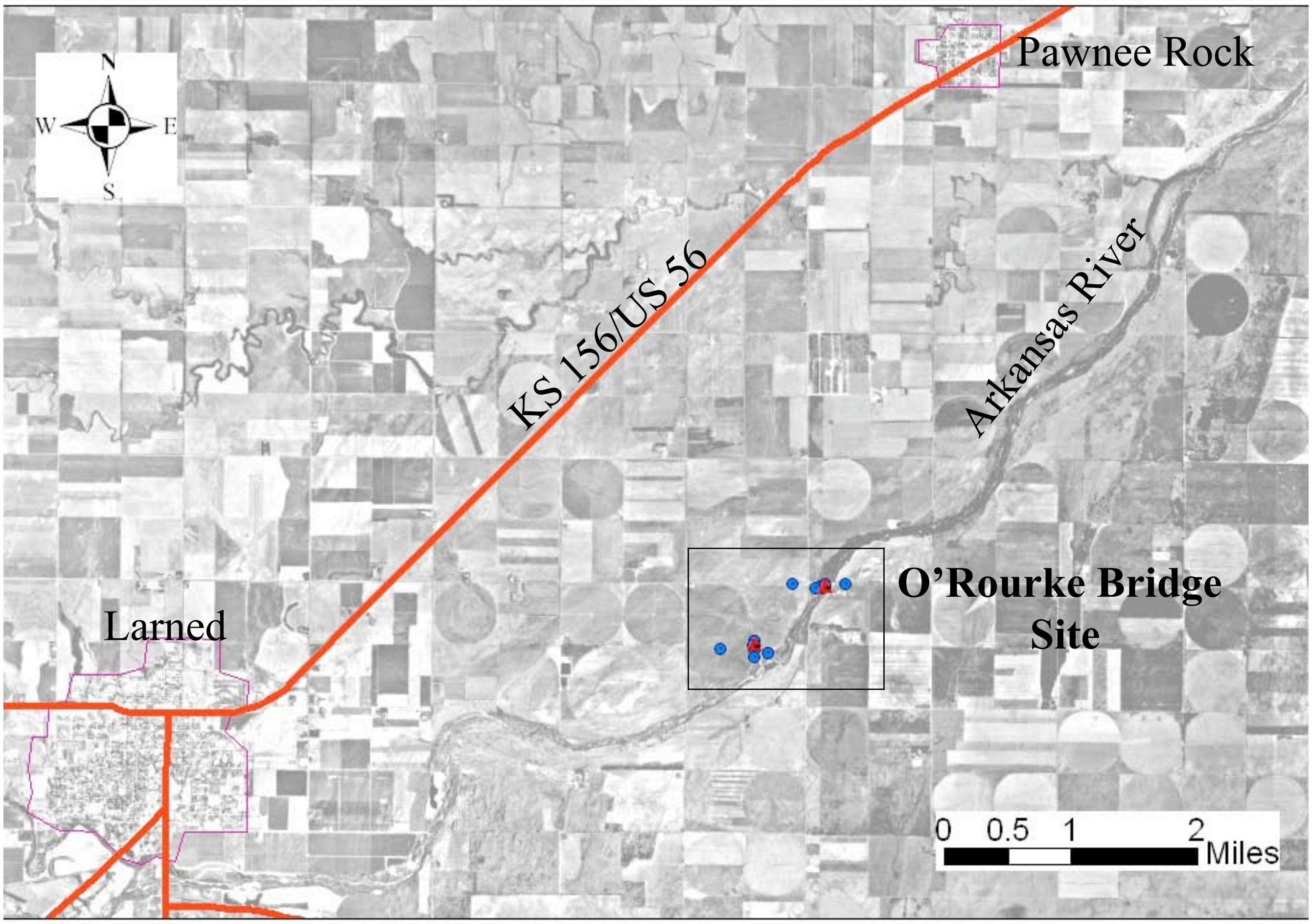


Figure 1a – Aerial photograph of the O'Rourke Bridge site and surrounding areas (red triangles indicate positions of pumping wells IW and LEA2, blue circles indicate positions of observation wells).

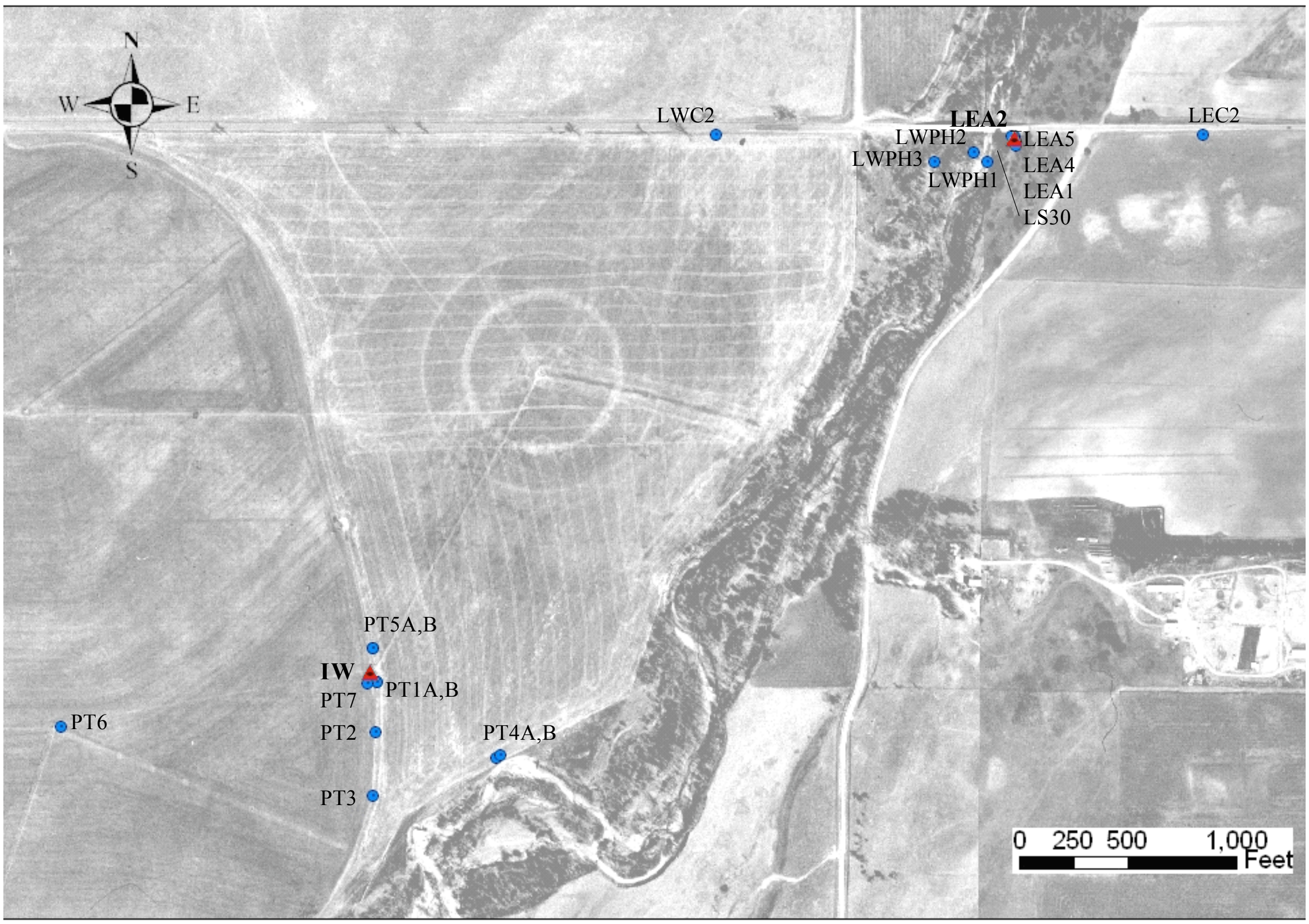


Figure 1b – Aerial photo of well network at the O'Rourke Bridge site (red triangles indicate positions of pumping wells IW and LEA2, blue circles indicate positions of observation wells).

Electrical Conductivity Profiling

The technique used in this project for stratigraphic delineation and selection of screened intervals for the observation wells was a direct-push method commonly referred to as electrical-conductivity profiling (Christy et al., 1994; Butler et al., 1999; Schulmeister et al., 2003). This approach is effective in defining subsurface lithology in unconsolidated alluvial sediments. The electrical-conductivity (EC) probe used in this work (Geoprobe SC 400) was designed such that the investigator can select different configurations to adjust the lateral extent of investigation. The configuration that gave the greatest lateral penetration (Wenner array) was used here.

The EC probe was advanced into the subsurface with a track-mounted Geoprobe 66DT unit using hydraulic pressure and a percussion hammer, while the electrical conductivity of the subsurface was measured at intervals of 0.05 ft. In this work, the electrical conductivity of the unconsolidated sediments was assumed to be primarily a function of grain size. Thus, low values of electrical conductivity were assumed to indicate sand and gravel, intermediate values were assumed to indicate silt, and high values were assumed to indicate clay. Although no cores were taken to confirm the assumed relationships, previous work at a KGS research site in the Kansas River floodplain has shown the general viability of these relationships (Butler et al., 1999; Schulmeister et al., 2003).

At most locations, the EC probe was advanced through the High Plains aquifer into the underlying clay unit. At three locations where only shallow observation wells were planned, EC profiling was terminated in the confining layer underlying the alluvial aquifer (observation wells PT2 and PT7) or at a depth of six meters (LS30). The information obtained by the EC logs was the only means of lithologic interpretation used in this work because the well installation procedure did not produce drill cuttings for visual inspection and description, and no cores were taken.

The direct-push electrical conductivity profile and interpreted stratigraphy for well nest PT1 is shown in Figure 2. This profile, which is a reasonable representation of the stratigraphy across the site, shows the three major units that exist in the shallow subsurface in the vicinity of the O'Rourke Bridge. The alluvial aquifer extends from the water table to the top of the confining layer, and is characterized by intermittent clay lenses, particularly in the lower two-thirds of its vertical extent. More details concerning this aquifer will be provided in the section on the S2002 test. Note that the depth to the water table varies across the site from less than three feet immediately adjacent to the Arkansas River channel at well LWPH1 to over 11 feet at wells PT1 and PT5. The confining layer was observed in all profiles obtained at the site. The thickness of the layer varies across the site from 10.3 to 21.8 ft with no apparent directional pattern. The High Plains aquifer is characterized by intermittent clay lenses, particularly in its upper half. The thickness of sands in the High Plains aquifer varies across the site from 9.6 to 22.4 ft with an apparent thinning on the east side of the site.

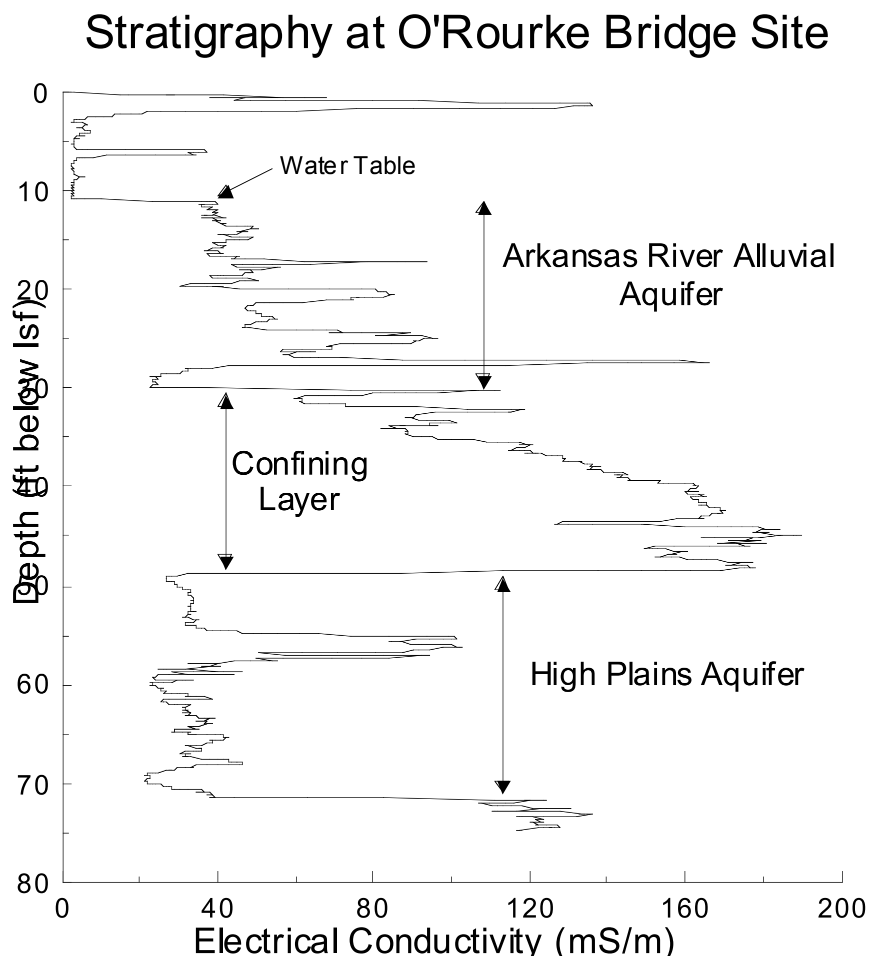


Figure 2 – Generalized stratigraphy at O'Rourke Bridge site determined from direct-push electrical conductivity profiling.

Well Construction

Eleven temporary observation wells were installed for this project to supplement the permanent monitoring wells in the KGS network at the O'Rourke Bridge site. At all well locations, an EC profile was obtained prior to well installation. All of the temporary wells were constructed in the same manner with the KGS Geoprobe unit (66DT). The unit was used to drive 2.125-inch (outer diameter) flush-joint steel pipe with an expendable drive point to the desired depth. Upon reaching that depth, the expendable point was knocked out the bottom of the pipe after the pipe had been flooded with potable water to prevent sand heave. The total depth inside the pipe was measured to ensure correct well screen placement.

Ten of the wells were constructed of 1.0-inch (Sch. 40 PVC) flush-joint casing with 1.0-inch (Sch. 40 PVC) 20-slot screen with a well point at the lower end. The other temporary well

(LS30) was constructed of 1.0-inch steel casing and screen. The casing string was assembled as it was lowered through the center of the 2.125-inch pipe. After the casing string, with the screen and well point at its lower end, was lowered to the bottom, the pipe was retracted. The unconsolidated formation collapsed back against the casing and screen as the pipe was removed. Retraction of the 2.125-in pipe continued until the bottom of the pipe string was adjacent to a zone where an annular seal was necessary. Bentonite slurry was then poured into the annular space between the inner diameter of the steel pipe and the outer diameter of the casing. After the 2.125-inch pipe was removed from the hole, bentonite chips were poured into the borehole to fill the remaining annular space to the land surface.

Tables 1 and 2 summarize well details for the temporary and permanent monitoring wells used in this study. The thicknesses of the various units were determined from the EC logs assuming that electrical conductivity values less than 45-50 mS/m correspond to sands. Note that as of the writing of this report, nine of the eleven temporary wells had been removed and the holes plugged.

Well Development

The completed wells were developed by airlifting with flow rates of over 10 gallons per minute. Development continued until groundwater turbidity was judged minimal. Slug tests were performed at all wells to assess the sufficiency of development activities. These tests demonstrated that the wells were in good hydraulic connection with the aquifer in which they were screened.

Table 1. Well construction and stratigraphy (from electrical conductivity logging) information for wells used in September 2002 pumping test.

Well	Well depth, ft bls[1]	Well radius, ft[2]	Screened interval, ft bls	Thickness of High Plains aquifer, ft[3]	Thickness of confining layer, ft	Thickness of upper sand in alluvial aquifer, ft	Thickness of possible barrier in alluvial aquifer, ft	Total thickness of alluvial aquifer, ft[4]
Alluvial aquifer								
LEA1[5]	17.2	0.09	4.7-16.7					
LEA2[5]	16.5	0.17	11.4-16.2					
LEA4[5]	30.6	0.09	25.3-30.0					
LWPH1	7.2	0.09	2.0-6.7	15.4	11.1	8.2	8.4	15.2
LWPH2	10.8	0.09	3.1-10.2	13.0	21.8	8.7	8.9	14.0
LWPH3	10.3	0.09	2.5-9.7	15.6	15.2	8.6	8.8	14.4
LS30[6]	18.1	0.04	14-18			8.1		
High Plains aquifer								
LEA5	69.6	0.17	59.5-69.2	15.4	13.5	7.6	6.6	15.2
LEB[7]				13.4	10.3	?[8]	8.8	?[8]

1 - feet below land surface; 2 – inner diameter of casing and screen; 3 – thickness of sand intervals within the High Plains aquifer; 4 – thickness of sand intervals in alluvial aquifer, water table position measured within an 18-hr period prior to pumping test; 5 – electrical conductivity profiling not performed at this location (within 30 ft of LEA5); 6 – electrical conductivity profiling terminated in possible barrier; 7 – electrical conductivity profiling only, no well – LEB located 436 ft to the east of LEA2; 8 – position of water table not known at time of test

Table 2. Well construction and stratigraphy (from electrical conductivity logging) information for observation wells used in October 2003 pumping test.

Well	Well depth, ft bls[1]	Well radius, ft[2]	Screened interval, ft bls	Thickness of High Plains aquifer, ft[3]	Thickness of confining layer, ft	Thickness of alluvial aquifer, ft[4]
Alluvial aquifer[5]						
PT1b	28.1	0.04	12.9-22.7			8.0
PT2	24.4	0.04	14.1-24.0			10.4
PT4b	25.1	0.04	14.9-24.7			16.2
PT5b	29.8	0.04	19.6-29.4			12.0
PT7[6]	24.9	0.04	14.6-24.5			
High Plains aquifer[7]						
PT1a	67.1	0.04	61.9-66.7	18.9	18.8	
PT3	67.1	0.04	61.9-66.7	17.1	18.2	20.6
PT4a	67.1	0.04	61.9-66.7	15.1	13.1	
PT5a	66.3	0.04	61.1-65.9	22.4	18.4	
PT6	66.9	0.04	61.7-66.5	15.8	21.8	6.6
LWC2	71.6	0.17	61.7-70.8	21.3	12.4	11.9
LEA5	69.6	0.17	59.5-69.2	15.4	13.5	16.8
LEC2	71.8	0.17	66.2-71.2	9.6	13.8	20.4

1 - feet below land surface; 2 – inner diameter of casing and screen; 3 – thickness of sand intervals within the High Plains aquifer; 4 – thickness of sand intervals in alluvial aquifer, water-table position measured within an 18-

hr period prior to test; 5 – thickness of High Plains aquifer and confining unit only provided if not listed elsewhere; 6 – electrical conductivity profiling not performed at this well; 7 – thickness of alluvial aquifer only provided if not listed elsewhere

PUMPING TESTS PROCEDURES AND RESULTS

Data Acquisition

Prior, during, and after both pumping tests, water levels were measured automatically with a variety of pressure transducers, and manually with electric tapes (Solinst and Heron). Use of the pressure transducers enabled changes in water levels to be monitored at a much higher frequency than would be possible by manual means. The rate at which transducer readings were acquired varied between tests and, in the case of the O2003 test, between observation wells. For the S2002 test, the rate varied from a measurement every second to a measurement every thirty seconds, with the highest acquisition rate occurring at the start of the test and in the initial portion of the recovery period. For the O2003 test, the rate varied from every 0.5 seconds to 5 minutes in the High Plains aquifer wells, and from 0.5 seconds to 15 minutes in the alluvial aquifer wells. After cessation of test monitoring, pressure measurement continued at the rate of a reading every 15 minutes in the permanent wells of the KGS monitoring network.

Butler (1998) emphasizes the importance of checking transducer operation in the field. For this project, transducer operation was checked through an in-field calibration. This was done by comparing pressure readings obtained with the transducers against electric tape measurements taken at the same time. The viability of a particular transducer was checked by performing a regression of transducer-measured water-level changes versus manually measured changes, and assessing the regression coefficient and standard error of the regression relationship. Figure 3 shows a typical regression relationship obtained through the in-field calibration. In this case, the relatively large standard error was apparently produced by operator error in the electric tape measurements. Tables 3 and 4 provide the sensor specifications and calibration results for the pressure transducers used in the S2002 and O2003 tests, respectively. Note that absolute pressure sensors were utilized in both tests, so atmospheric pressure was also recorded using a pressure sensor in the air column of a monitoring well at the site. The atmospheric pressure readings were subtracted from the records of the absolute pressure sensors prior to the regression analysis.

Additional measurements were made of pumping rate, precipitation, and water quality. The methods for monitoring pumping rate differed between tests, so those methods are described in later sections. Precipitation data were acquired at the USGS gaging station at O'Rourke Bridge using an electronic rain gauge. Water samples were periodically acquired during both tests as described in later sections.

Arkansas River Flow During Study Period

The study was originally designed to assess the impact of groundwater pumping on the flow of the Arkansas River near Larned. The pumping test in the alluvial aquifer was performed in September 2002 (from the 17th to the 19th) as scheduled in the contract. Although there was no flow in the river, the test provided data that were used to determine hydraulic and water-quality characteristics of the alluvial aquifer that could be used to assess the impact of groundwater pumping on the river if there had been flow. For example, the aquifer hydraulic properties determined from the test could be inserted into a stream-aquifer interaction model to predict the impact of pumping from the alluvial aquifer on the river flow.

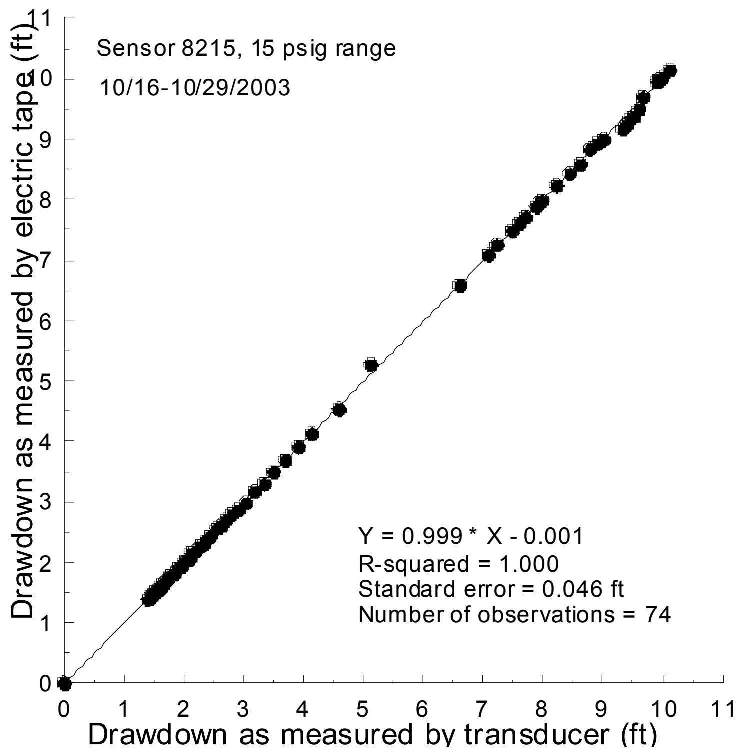


Figure 3 – Results of in-field calibration of pressure transducer in well PT1a.

Table 3. Specifications and calibration results for pressure transducers used in S2002 pumping test.

Well	Transducer Serial No.[1]	Transducer Range and Type[2]	Calibration Equation[3]	Adjusted Regression Coefficient	Standard Error (ft)	Number of Observations
Alluvial aquifer						
LEA1	5318 – IS/CS	20 psig	y = 1.014x + 0.007	0.997	0.008	56
LEA4	1752 – IS/MT	15 psig	y = 1.006x – 0.003	0.993	0.004	21
LWPH1[4]	8338 – IS/MT	30 psia				
LWPH2[4]	6814 – IS/MT	30 psia				
LWPH3[4]	6613 – IS/MT	30 psia				
LS30	5319 – IS/CS	20 psig	y = 0.974x + 0.024	0.986	0.014	51
High Plains aquifer						
LEA5	11424 – IS/MT	15 psig	y = 0.984x - 0.034	0.999	0.014	19

1 – IS/CS – In-Situ transducer with Campbell-Scientific 23X datalogger, IS/MT – In-Situ MiniTroll integrated transducer and data logger; 2 – psia – absolute pressure transducer, psig – gauge (relative to atmospheric pressure) pressure transducer; 3 – equation resulting from regression of transducer readings (x) versus electric tape measurements (y); 4 – drawdown was small at these wells and only four electric tape measurement were obtained during monitoring so regression was not attempted, available data indicate sensors behaved in a linear fashion.

Table 4 • Specifications and calibration results for pressure transducers used in O2003 pumping test.

Well	Transducer Serial No.[1]	Transducer Range and Type[2]	Calibration Equation[3]	Adjusted Regression Coefficient	Standard Error (ft)	Number of Observations
Alluvial aquifer						
PT1b	8173 – IS/CS	15 psig	y = 1.019x + 0.001	0.998	0.006	10[4]
PT2	31149 - GW	13 psig	y = 0.914x + 0.011	0.969	0.015	24
PT4b	31150 - GW	13 psig	y = 0.936x + 0.016	0.995	0.009	37
PT5b	5318 – IS/CS	20 psig	y = 0.977x – 0.006	0.991	0.009	10[4]
PT7	44799 – S/LL	21.8 psia	y = 0.904x – 0.005	0.983	0.010	9
High Plains aquifer						
PT1a	8215 – IS/CS	15 psig	y = 0.999x – 0.001	1.000	0.046	74
PT3	8484 – IS/MT	30 psig	y = 0.997x – 0.004	0.999	0.028	84
PT4a	44775 – S/LL	21.8 psia	y = 0.982x + 0.012 y = 1.019x – 0.191[5]	0.999 0.998	0.016 0.040	38 55
PT5a	5245 – IS/CS	10 psig	y = 1.046x + 1.334	0.992	0.214[6]	56
PT6	8518 – IS/MT	30 psig	y = 0.985x – 0.003	1.000	0.004	9[7]
LWC2	4640 – IS/MT	30 psig	y = 0.994x + 0.025	1.000	0.007	84
LEA5	11424 – IS/MT	15 psig	y = 1.026x + 0.004	0.999	0.012	37
LEC2	4620 – IS/MT	30 psig	y = 1.043x + 0.008	0.998	0.010	33

1 – IS/CS – In-Situ transducer with Campbell-Scientific 23X datalogger, IS/MT – In-Situ MiniTroll integrated transducer and data logger, S/LL – Solinst Levelogger integrated transducer and datalogger, GW – Global Water integrated transducer and datalogger; 2 – psia – absolute pressure transducer, psig – gauge (relative to atmospheric pressure) pressure transducer; 3 – equation resulting from regression of transducer readings (x) versus electric tape measurements (y); 4 – only observations prior to pump cut off were used because of apparent electrical noise after cutoff; 5 – apparent change in calibration relationship at 14:49:58 on 10/20/03 – reason for change is not known;
6 – source of large error in transducer readings is not known; 7 - observations in first four hours of pumping were not used because of uncertainty regarding time at which electric tape measurements were obtained

The High Plains aquifer pumping test was delayed in hopes of performing the test during a period of flow in the river. When it became apparent that there would not be sustained flow in the river, the test was scheduled and performed on October 20-24, 2003.

The flow in the Arkansas River was continuous (up to 3 ft^3/sec) from the beginning of 2002 until April 17 (Figure 4). From April 18 to June 29, the river alternated between dry and a mean daily flow of <0.7 ft^3/sec (peak flow of <2 ft^3/sec). Except for August 1-2, 2002, the river was dry from June 30, 2002 to September 8, 2003. A flow event occurred during September 9-25, 2003; the flow reached a peak of 174 ft^3/sec and averaged 160 ft^3/sec on September 16, 2003. The source of the flow was the Pawnee River, which received runoff from an intense rainstorm over the tributary watershed of Buckner Creek and its tributary, Saw Log Creek. The Arkansas River remained dry from September 26 through the end of 2003.

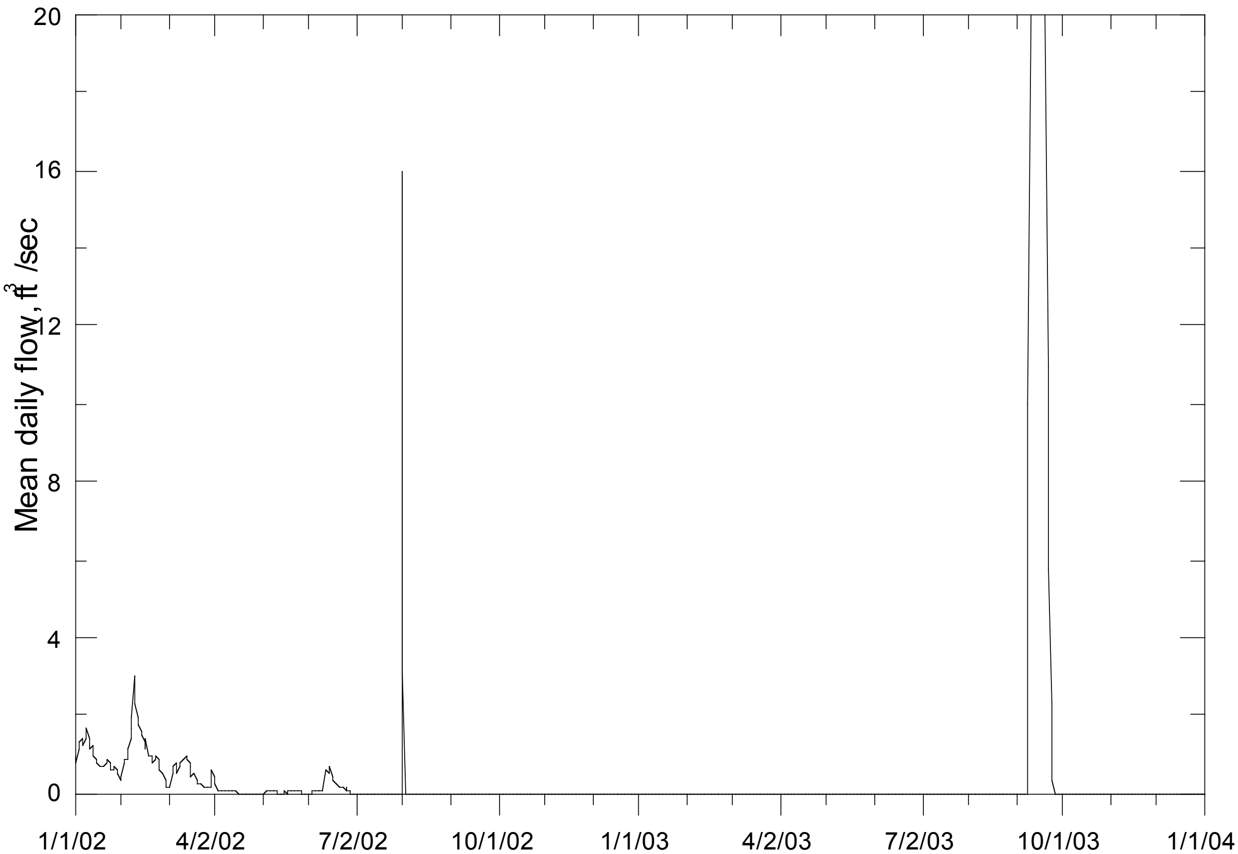


Figure 4. Mean daily flow of the Arkansas River at the O'Rourke Bridge during 2002-2003. The mean daily flow reached a peak of 160 ft^3/sec during the flow event of September 2003.

September 2002 (S2002) Pumping Test

Well LEA2 (see Figure 1b) was pumped at an approximately constant rate of 23.0 gallons per minute (gpm) from 8:40:35 on September 17, 2002 to 10:47:22 on September 19, 2002. The total duration of the pumping period was 50.11 hours (180,407 secs). After the pump was cut off, water levels were monitored at all wells for another six hours, after which monitoring continued only in the permanent wells in the KGS network at the O'Rourke Bridge site. No precipitation occurred in the 48 hours prior to the test or during the pumping period. A small amount of precipitation (0.12 inches) occurred after the end of the test on September 19, but no further precipitation was recorded during the recovery period. Note that all clock times for the S2002 test are given in Central Daylight Time.

The pumping rate was monitored using an electronic paddlewheel flowmeter (Omega FP-5800) connected to a datalogger (Campbell-Scientific 23X). The acquisition rate varied from a measurement every second to a measurement every thirty seconds, with the highest acquisition rate occurring at the start of the test. Flowmeter performance was manually checked at six times spaced over the duration of the test using a 5.4-gallon bucket and a stop watch. At least two flow-rate measurements were obtained each time. Figure 5 is a plot of the pumping rate obtained with the electronic flowmeter (calibrated using the bucket measurements) versus time. After the first 200 seconds of pumping, the pumping rate was essentially constant for the remainder of the test. The pumped water was discharged into the dry channel of the Arkansas River approximately 400 feet downstream from well LEA2.

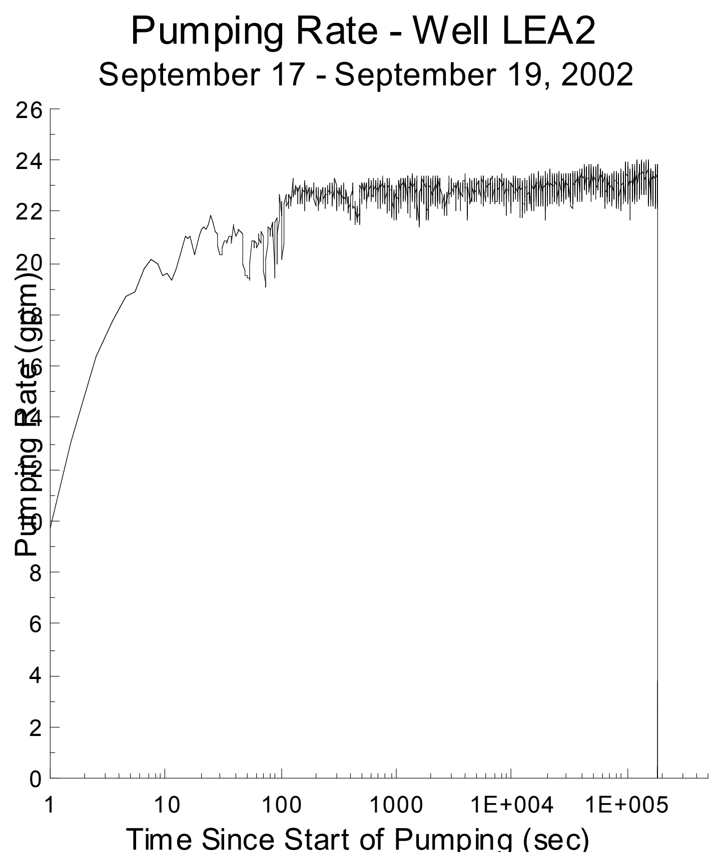


Figure 5 – Pumping rate versus time for S2002 Test.

Well LEA2 and all but one of the alluvial aquifer observation wells were screened in the upper portion of the aquifer, above a clay and silt zone that may act as a barrier to vertical flow (Figure 6). Well LEA4 was the only observation well screened in the lower portion of the alluvial aquifer. Table 5 lists the distances from LEA2 to the seven observation wells.

Monitoring Data

Monitoring at wells LEA1 and LS30 commenced an hour prior to the pumping test and concluded six hours after the cessation of pumping (Figures 7 and 8). A longer period of monitoring was not attempted at these wells because of concerns about vandalism of the datalogger that was on the land surface near the wells. Although a temporal trend in water levels

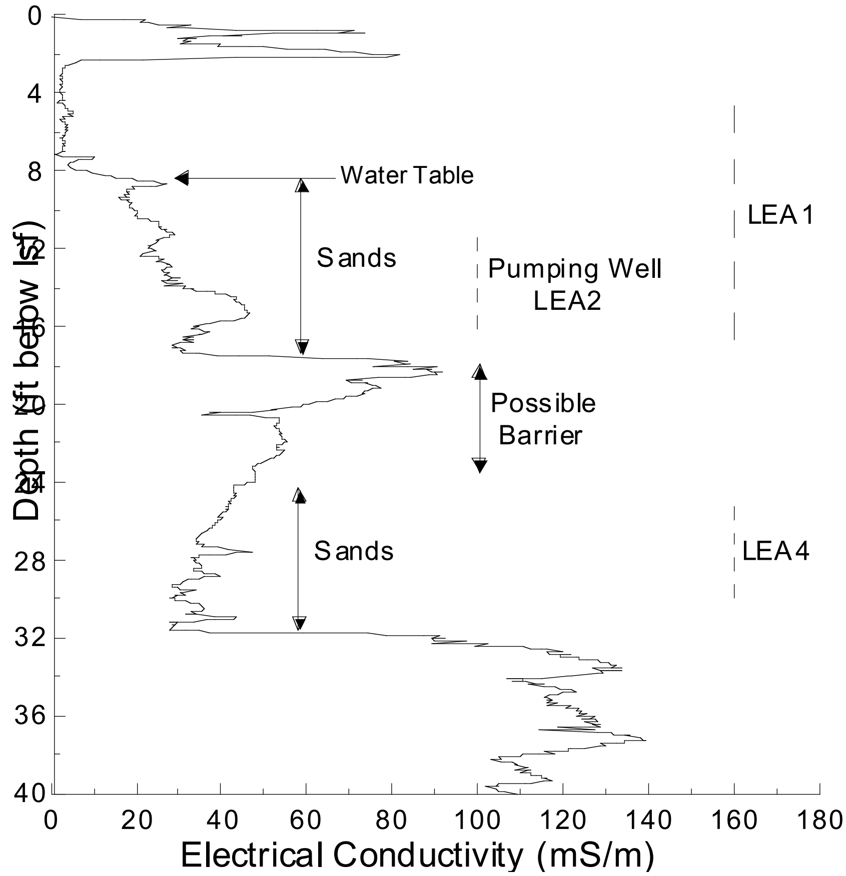


Figure 6 – Expanded view of the shallow stratigraphy in the vicinity of the LEA well nest

Table 5. Distances from pumping well LEA2 to observation wells used in S2002 test.

Well	Distance from well LEA2, ft[1]
Alluvial aquifer	
LEA1	14.2
LEA4[2]	18.1
LWPH1	161.0
LWPH2	198.0
LWPH3	384.6
LS30	30.3[3]
High Plains aquifer	
LEA5	16.5

1 - distances determined from surveying performed in March of 2004; 2 – screened below barrier in alluvial aquifer;
3 – distance determined by tape measure in September of 2002

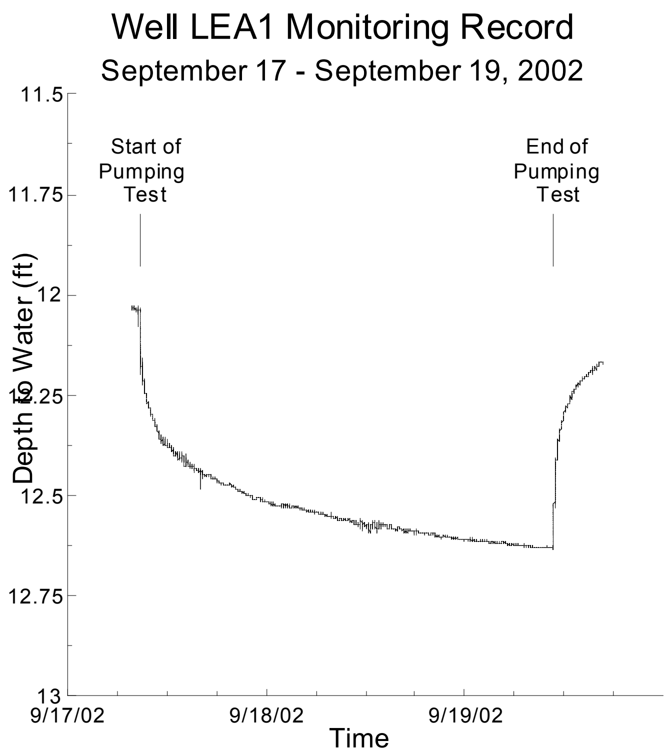


Figure 7 – Depth to water at well LEA1

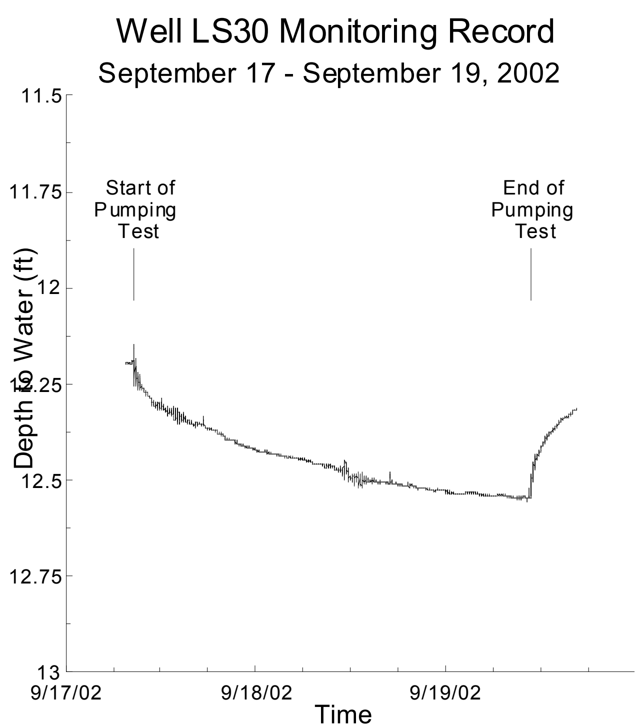


Figure 8 – Depth to water at well LS30

could not be determined from the monitoring record at these wells, a decline of approximately 0.01 ft/day was estimated from the other wells in the alluvial aquifer. This magnitude of decline would have a minimal effect on drawdown measured at wells LEA1 and LS30. Only the later portion of the recovery data would be expected to be affected by the decline.

Monitoring at well LEA4 commenced the day prior to the pumping test and continued after the test as part of the KGS monitoring program (Figure 9). A temporal decline in water level of approximately 0.01 ft per day can be observed in the data following the recovery period. The diurnal fluctuations in water level following the recovery period are a product of phreatophyte activity (Butler et al., 2004). The rise in water level prior to the test is undoubtedly also a product of phreatophyte activity.

Monitoring at wells LWPH1, LWPH2, and LWPH3 started in August of 2002 and continued after the test as part of the KGS monitoring program (Figures 10 and 11). A temporal decline in water level approaching 0.01 ft per day can also be observed in these data following the recovery period. The impact of the pumping test on well LWPH3 is barely discernible. In the other two wells, drawdown is discernible but the diurnal fluctuations produced by phreatophyte activity introduce considerable noise into the drawdown data.

The monitoring record from the High Plains aquifer monitoring well (LEA5) indicates that pumping activity in the High Plains aquifer made it difficult to discern any effects of pumping in the alluvial aquifer (Figure 12). Drawdown due to pumping in the High Plains aquifer was occurring prior to the start of the pumping test and continued through the first 12 hours of the test. At approximately 9 PM on 9/17, a well in the High Plains aquifer ceased pumping and the water levels started to recover. Recovery continued until a well started pumping at approximately 8 AM on 9/18. Drawdown continued until approximately 8 PM on 9/19, after which water levels recovered until the end of the monitoring period.

Drawdown Analysis

Wells LEA1 and LS30 were chosen as the primary wells for use in the analysis because the magnitude of the drawdown at those wells was large compared to temporal trends and measurement noise. The Moench (1997) model for pumping tests in unconfined aquifers was chosen for the analysis of the drawdown data. The Moench model is an extension of the widely used model of Neuman (1974). The major additions of the Moench model are the incorporation of wellbore storage at the pumping well and of non-instantaneous drainage of water from the unsaturated zone. In addition, the computational efficiency of the procedures used to evaluate the mathematical functions is significantly improved over the model of Neuman. The implementation of the Moench model in AQTESOLV, an automated well-test analysis package (HydroSOLVE, 2001), was used here.

The analysis of the LEA1 data produced an excellent fit to the drawdown data (Figure 13) for a transmissivity (T) of 3740 ft^2/day, a specific yield (S_y) of 0.16, and an anisotropy ratio (vertical component of hydraulic conductivity (K_z) over horizontal component of hydraulic conductivity (K_x)) of 0.06-0.2. The differences between the measured drawdown and the model in the first 100 seconds of the test are due to mechanisms that are not included in the Moench

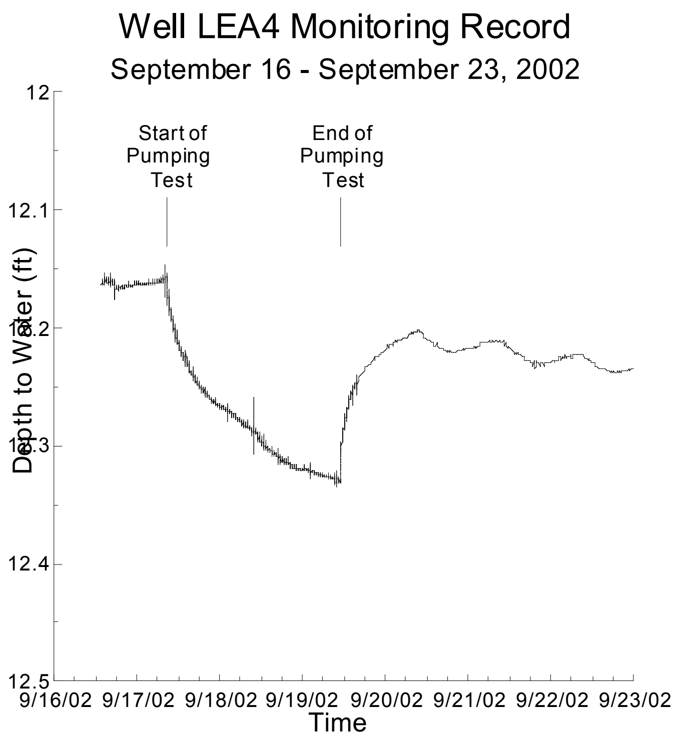


Figure 9 – Depth to water at well LEA4

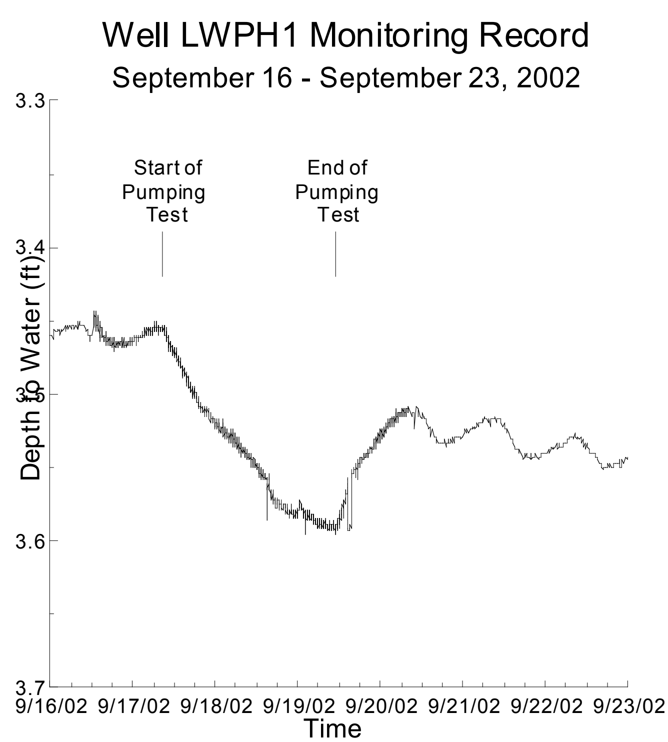


Figure 10 – Depth to water at well LWPH1

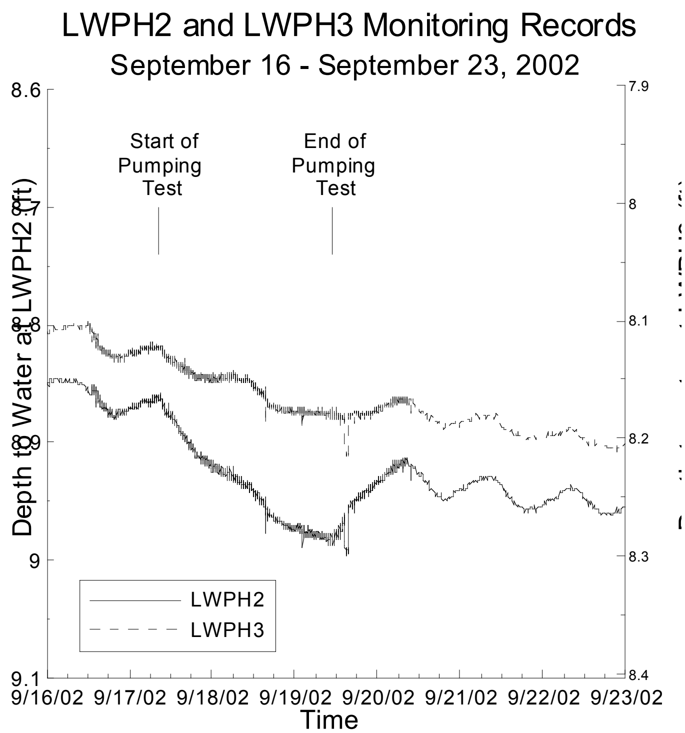


Figure 11 – Depth to water at wells LWPH2 and LWPH3.

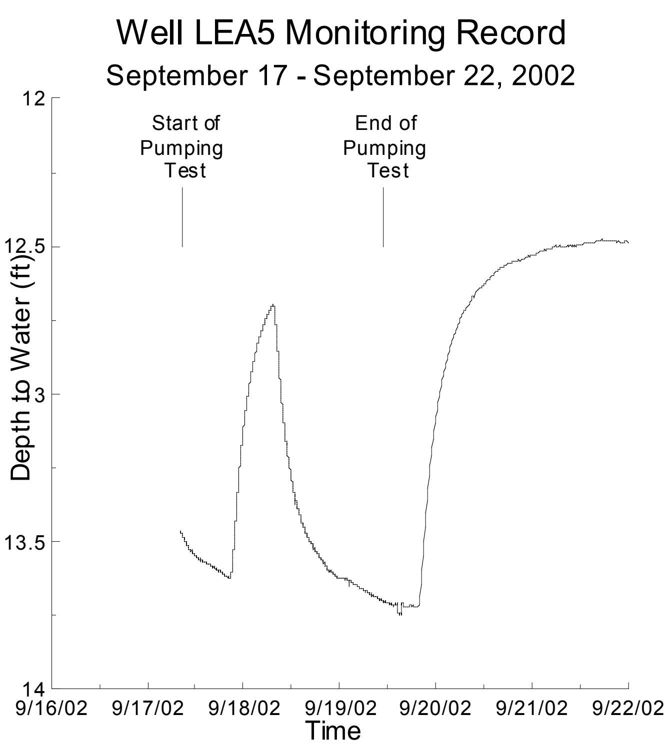


Figure 12 – Depth to water at well LEA5.

model. The differences in the later portions of the recovery period may have been a result of discharging the pumped water too close to the test site. The transmissivity estimate was checked by using the Theis recovery method (Kruseman and de Ridder, 1990) to analyze the later portions of the recovery data. The T estimate from the recovery analysis was 4000 ft^2/day, which is within 7% of the estimate from the Moench model. An estimate of the storage coefficient (0.0156) was also obtained using the Moench model, but little significance should be attached to that value because of its dependence on the early time data that are affected by mechanisms not incorporated in the Moench model. Note that the semilog straight-line relationship observed in the later portions of the pumping period indicate that lateral hydraulic boundaries are not affecting the test data. In addition, there is no indication of flow from the underlying High Plains aquifer.

The drawdown from well LS30 proved more difficult to analyze because of small shifts in transducer position that occurred during the test (Figure 14). These shifts coincided with times at which electric tape measurements were taken in the small-diameter well. Adjustments for these shifts were difficult to make, so the electric tape data were used in the analysis. The analysis of the electric tape data from well LS30 produced a very good fit to the drawdown data (Figure 15) for a T of 3850 ft^2/day and a S_y of 0.31. The data were not of sufficient quality to estimate the storage coefficient or the anisotropy ratio. As with the data from well LEA1, the drawdown data at well LS30 show no indication of lateral hydraulic boundaries or vertical flow from the underlying High Plains aquifer.

The T estimates obtained from analysis of drawdown data from wells LEA1 and LS30 are quite similar, so the average of the two values (3800 ft^2/day) would appear to be a reasonable estimate of transmissivity in the vicinity of the LEA well nest. This estimate, however, is of little value for studies not focused on the LEA well nest, because transmissivity is a vertically integrated quantity and thus dependent on the thickness of the aquifer in the area of interest. A more useful quantity is hydraulic conductivity, which characterizes the transmissive nature of a unit volume of the aquifer. The horizontal component of hydraulic conductivity (K_x) can be estimated by dividing the transmissivity by the aquifer thickness. In this case, however, there is uncertainty about the thickness of the alluvial aquifer. The thickness could be that of the sands above the possible barrier depicted in Figure 6, or it could be the total thickness of sands above the confining layer. Using Table 1, an average thickness of 8.2 ft can be obtained for the thickness of sands above the possible barrier. This would result in a K_x estimate of 460 ft/day, which would be on the upper end of the hydraulic conductivity range for sands. The average total thickness of sands in the alluvial aquifer is 14.7 ft, which would result in a K_x estimate of 260 ft/day, which is consistent with slug tests performed in the upper portions of the alluvial aquifer.

The S_y estimates obtained from analysis of drawdown at wells LEA1 and LS30 differed by close to a factor of two. This difference may be produced by aquifer heterogeneity. Butler (1988) and Sanchez-Vila et al. (1999) discuss how the storage estimate can be affected by heterogeneity in hydraulic conductivity. A zone of higher-than-average hydraulic conductivity between wells LEA2 and LEA1 would produce a smaller S_y estimate at well LEA1 because the pressure disturbance would propagate to the well faster than would have occurred with the

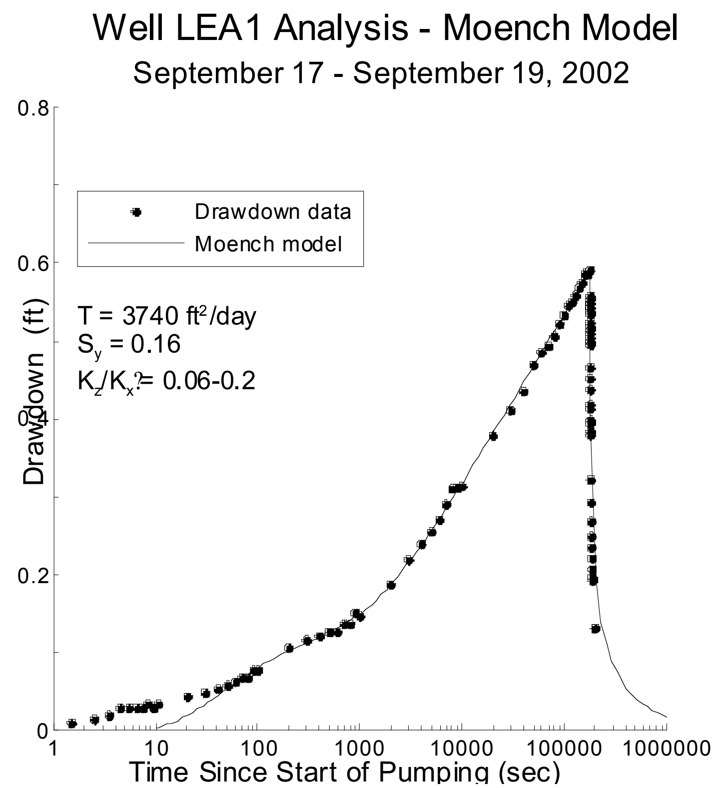


Figure 13 – Results of analysis of LEA1 drawdown data with Moench model

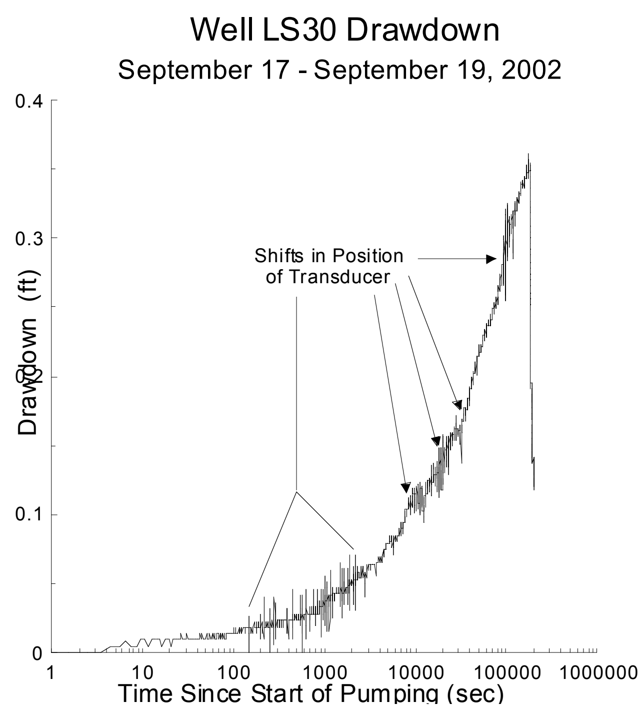


Figure 14 – Noise in transducer measurements at well LS30.

average aquifer properties. Geochemistry data collected at the site are consistent with an interpretation of a zone of higher conductivity between wells LEA1 and LEA2.

Drawdown data from well LEA4 were analyzed in an attempt to obtain more insight into the appropriate values to use for K_x and S_y. As shown in Figure 6, well LEA4 was screened below a zone that could serve as a barrier to vertical flow. This zone increased the complexity of the analysis because the Moench model does not incorporate heterogeneity in hydraulic conductivity. Thus, the fit was expected to be inferior to those obtained at wells LEA1 and LS30, particularly in the initial portion of the test and the recovery period. When the period from 30,000 seconds to the end of the pumping test was emphasized in the analysis and the T estimate was assumed known (3800 ft^2/day), a reasonable fit was obtained for the later portion of the pumping test (Figure 16). These results indicate that the full thickness of the aquifer should be used to obtain the K_x estimate, and that the S_y value obtained from well LS30 is probably the more appropriate estimate for the specific yield. Note that the anisotropy ratio reflects the existence of the possible barrier, but the quality of the data is not sufficient to have great confidence in that anisotropy estimate.

Summary

The results of the S2002 pumping test indicate that reasonable estimates for the transmissivity and specific yield of the alluvial aquifer in the vicinity of well LEA2 are 3800 ft^2/day and 0.31, respectively. The T estimate corresponds to a hydraulic conductivity value of 260 ft/day because the total thickness of sands in the alluvial aquifer appears to be contributing flow to the pumping well. The drawdown data show no indication of hydraulic boundaries or leakage from the underlying High Plains aquifer.

Unfortunately, there was no flow in the Arkansas River at the time of the S2002 pumping test. Without repeating the test when there is flow in the river, the nature of the relationship between the alluvial aquifer and the Arkansas River cannot be unequivocally established. Despite that, given the parameter estimates determined from the test, we can confidently state that pumping near the Arkansas River will affect flow in the river. However, for pumping wells located more than a few hundred feet from the river, the timing of that impact will significantly lag the timing of the pumping because the relatively large value for specific yield will slow the propagation of the pumping disturbance.

Trends in water levels, most likely produced by phreatophyte activity and pumping in the High Plains aquifer, made it difficult to derive much insight from pumping-induced responses in the more distant observation wells (LWPH1, LWPH2, and LWPH3). Repeating the test during the early spring before phreatophyte activity and pumping in the High Plains aquifer have commenced, and increasing the duration of the test would enable the drawdown at those wells to be utilized in the analysis. Although the diameter of well LEA2 limits the size of the pump that can be used, a larger pump could be employed to increase the pumping rate by at least 50%, and therefore improve the signal to noise ratio of the drawdown data at the more distant wells.

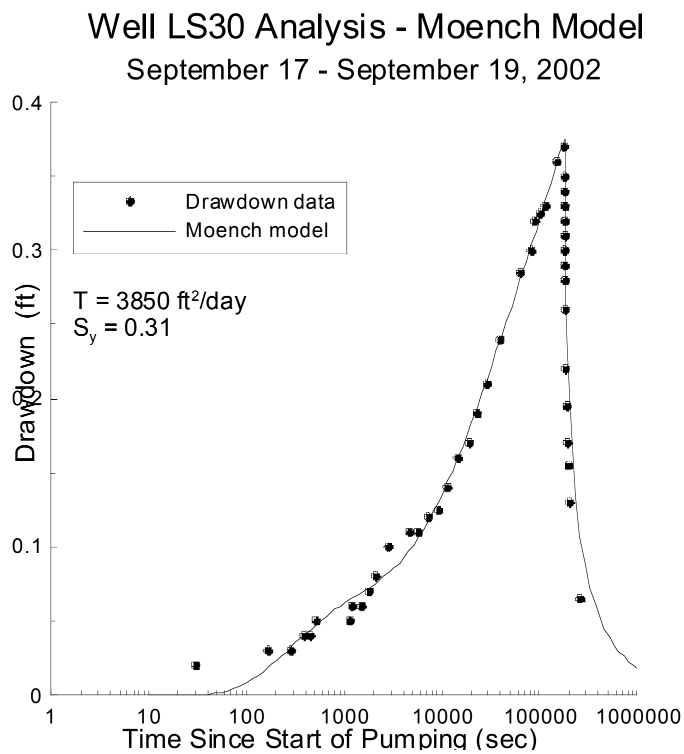


Figure 15 - Results of analysis of LS30 drawdown data with Moench model.

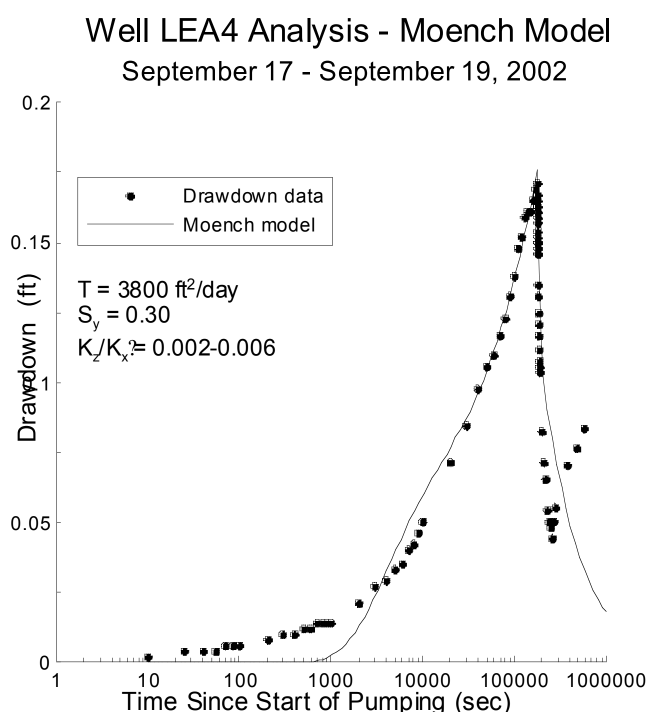


Figure 16 – Results of analysis of LEA4 drawdown data with Moench model.

October 2003 (O2003) Pumping Test

Well IW was pumped beginning at 10:18:48 AM on October 20, 2003. The well was pumped for approximately 16 minutes to check operation and fill the subsurface pipe that extended 1584 ft northeast to the central pivot irrigation system through which the water was discharged. The pump was shut down at 10:34:26 AM for repairs and to make final test preparations. The main period of pumping began at 11:05:09 AM on October 20 and continued until 10:13:13 AM on October 24, 2003. The total duration of the main pumping period was 95.13 hours (342,484 secs). After the pump was cut off, water levels were monitored at all wells for another five to eighteen days, after which monitoring continued only in the permanent wells in the KGS network at the O'Rourke Bridge site. No precipitation occurred in the week prior to the test, during the pumping period, or in the week following the cessation of pumping. Note that all clock times for the O2003 test are given in Central Standard Time.

The pumping rate was monitored using an existing totalizing flowmeter mounted at the base of the central pivot. The flowmeter was positioned near bends and a diameter change in the discharge pipe, so the measurements were impacted by those features. Totalizer readings were taken frequently in the first five hours of pumping in an attempt to record the rate variations early in the test. Personnel from the Division of Water Resources measured the flow rate at three times during the test (afternoons of October 20 and 21, and morning of October 24) using an ultrasonic flowmeter (Panametrics PT868). Figure 17 is a plot of flow rate versus time for the entire period of pumping that is based on a combination of the totalizer and ultrasonic flowmeter readings. The pumping rate varied considerably in the first 4200 seconds but then was maintained at a near constant rate of 358 gpm until the last 20 seconds of the test when the pump motor was inadvertently revved up prior to shut off.

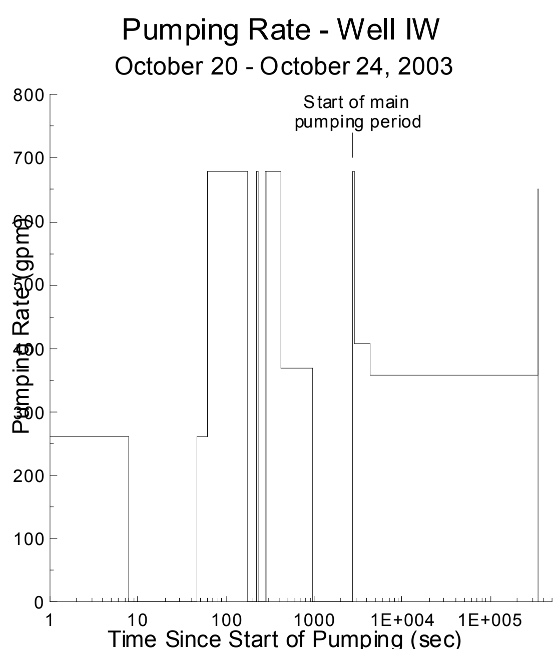


Figure 17 – Pumping rate versus time for O2003 test.

Well construction details for pumping well IW are not available, so the exact position of the screened interval within the High Plains aquifer is not known. Based on standard construction practices for irrigation wells at the time well IW was drilled, the radius of the screen is estimated to be 1.33 ft. The gravel pack is assumed to extend upward through the overlying confining unit into the alluvial aquifer, forming a conduit through the confining layer. The impact of this conduit will be discussed in later sections.

Figure 1b provides an areal view of the observation well network used in the O2003 test and Table 2 provides details concerning the construction of the individual observation wells. All of the observation wells in the High Plains aquifer were screened in the middle to lower portions of the aquifer (below 60 ft in Figure 2), and most of the observation wells in the alluvial aquifer were screened across the middle portions of that unit (15-25 ft in Figure 2). Table 6 lists the distances from pumping well IW to the 13 observation wells.

Table 6. Distances from pumping well IW to observation wells used in O2003 test

Well	Distance from pumping well, ft[1]
Alluvial aquifer	
PT1b	55.2
PT2	276
PT4b	653
PT5b	115.8
PT7	47.9
High Plains aquifer	
PT1a	54.2
PT3	564
PT4a	655
PT5a	115.7
PT6	1450
LWC2	2802
LEA5	3856[2]
LEC2	4568[2]

1 - distances determined from tape or calibrated wheel measurements in October of 2003; 2 – distance determined using tape measurements and March 2004 surveying data

Monitoring Data – High Plains aquifer wells

Monitoring at well PT1a began at 10:45 AM on October 16, 2003 and concluded at 12:15 PM on November 11, 2003 (Figure 18). However, no data could be used beyond November 4 because of datalogger malfunctioning. The malfunctioning may have been a result of mounting the datalogger on a fence post through which electric current was run to constrain cattle in early November. No temporal trend could be detected in the data.

Monitoring at well PT3 began at 8:15 AM on October 16, 2003 and concluded at 11:45 AM on November 11, 2003 (Figure 19). A very slight decline in water level (less than 0.05 ft over the entire monitoring period) was observed. This decline was ignored as it was very small relative to the drawdown and would only impact the later stages of the recovery data.

Monitoring at well PT4a began at 9:15 AM on October 16, 2003 and concluded at 2:45 PM on November 11, 2003 (Figure 20). No temporal trend could be detected in the monitoring data.

Monitoring at well PT5a began at 6:30 PM on October 15, 2003. However, the original pressure transducer malfunctioned so the transducer was replaced and monitoring restarted on 9:45 AM on October 20. Monitoring continued until 12:15 PM on November 11, 2003 but electrical noise began to impact the data shortly after the pump was cut off on October 24 (Figure 21). No data were available after October 30. The noise in the transducer readings is thought to have been caused by datalogger malfunctioning. A broken ground wire was found on October 29, consistent with the noise that was observed in the data.

Monitoring at well PT6 began at 12:30 PM on October 16, 2003 and concluded at 2:10 PM on October 29, 2003 (Figure 22). Monitoring was concluded at that time because cattle were released into the pasture in which well PT6 was located, so the equipment was removed to prevent damage. A pronounced increase in water level was observed in well PT6 over the course of the monitoring period. The cause of this increase could not be determined.

Monitoring at well LWC2 began in 2001 and continued after the test as part of the KGS monitoring program (Figure 23). A small increase in water level was observed over the monitoring period, as were the effects of nearby pumping activity.

Monitoring at well LEA5 began in September of 2002 and continued after the test as part of the KGS monitoring program (Figure 24). A small increase in water level was again observed over the monitoring period, as were the effects of nearby pumping activity.

Monitoring at well LEC2 began in 2001 and continued after the test as part of the KGS monitoring program (Figure 25). The impact of nearby pumping activity is very clearly displayed in the monitoring record of well LEC2. The impact of this activity diminished to the south and west (Figures 18-24), so it was assumed that the pumping activity was occurring to the north and east of the O'Rourke Bridge site. The locations of the pumping wells that are responsible for the features noted on Figure 25 could not be determined.

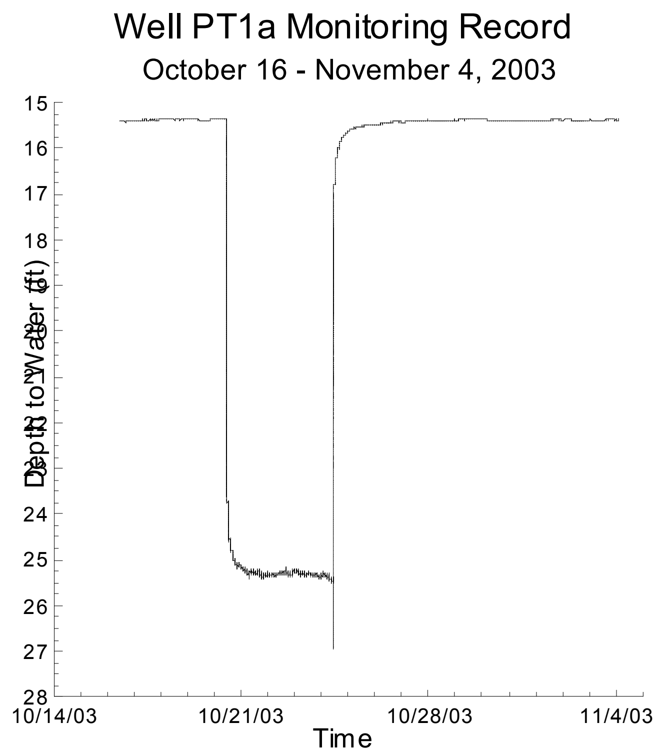


Figure 18 – Depth to water at well PT1a.

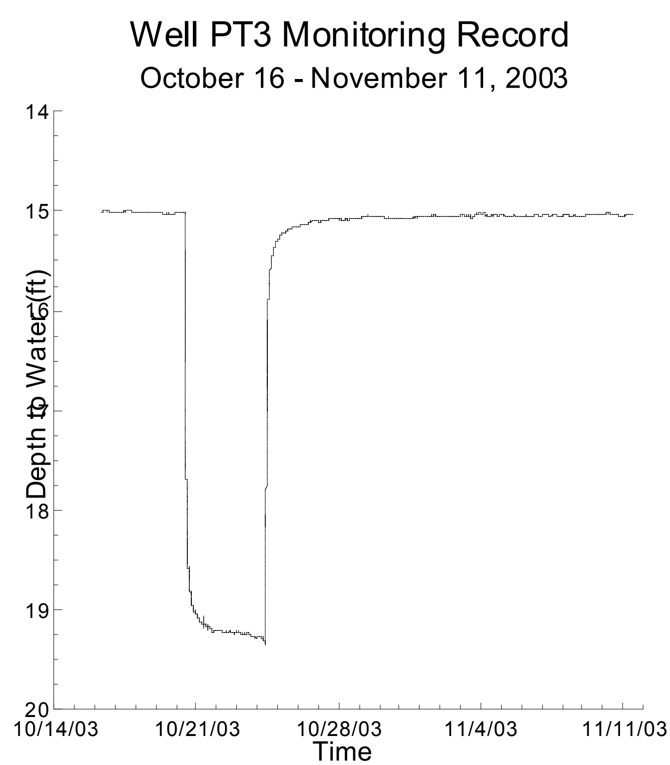


Figure 19 – Depth to water at well PT3.

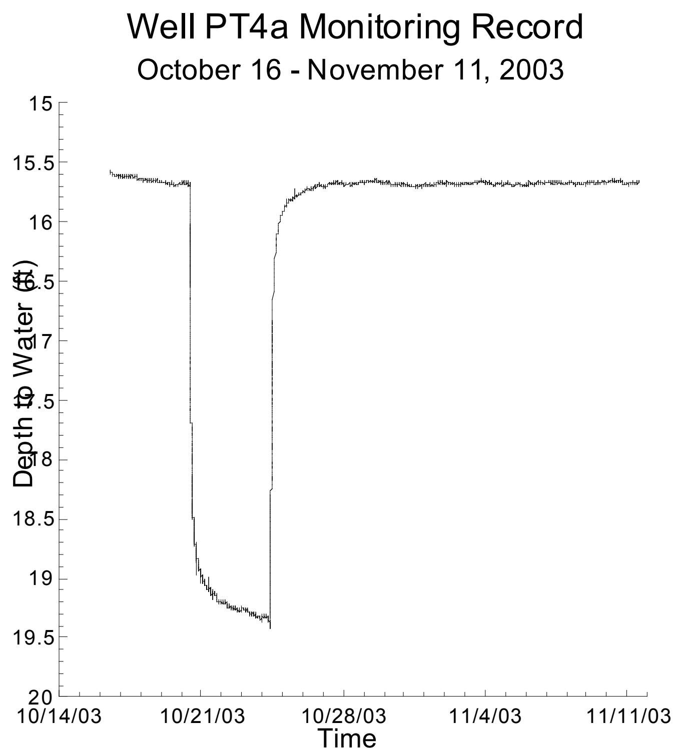


Figure 20 – Depth to water at well PT4a.

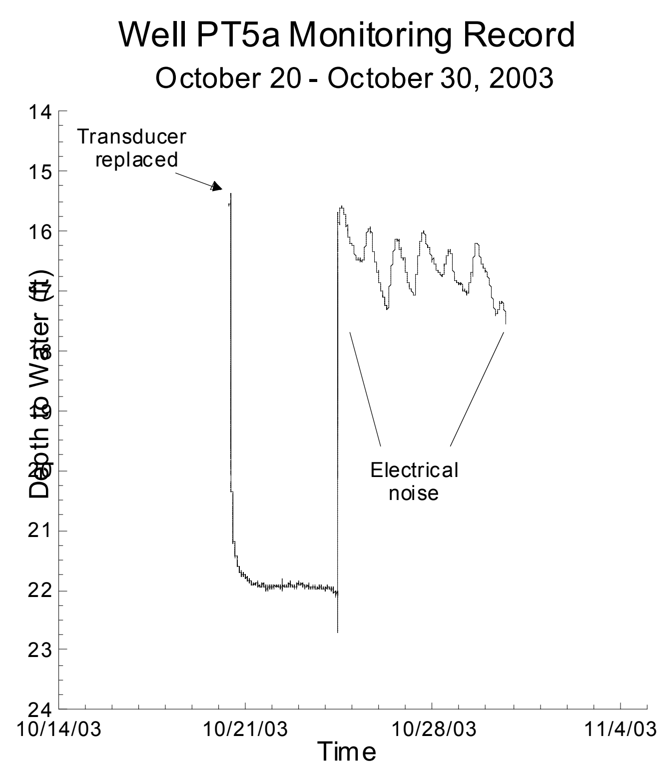


Figure 21 – Depth to water at well PT5a.

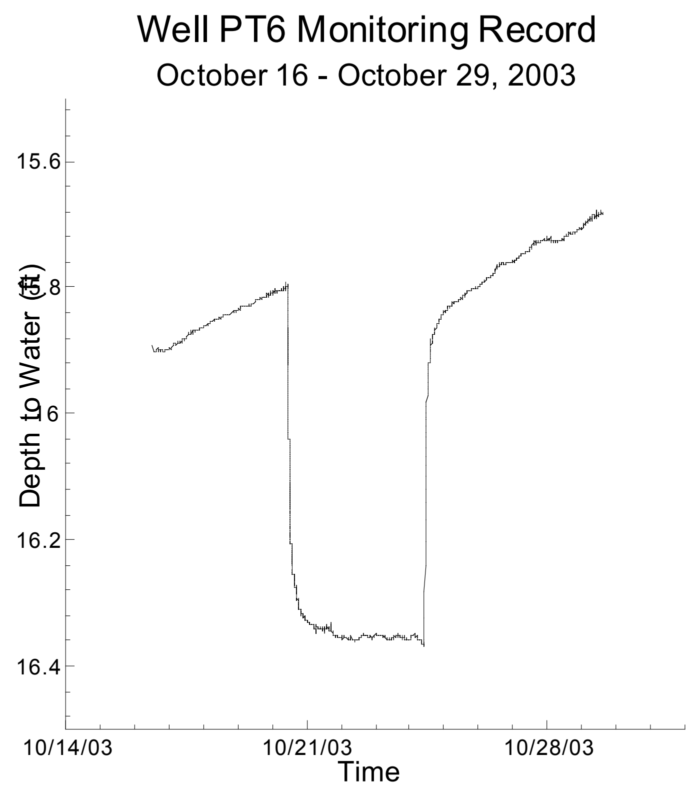


Figure 22 – Depth to water at well PT6.

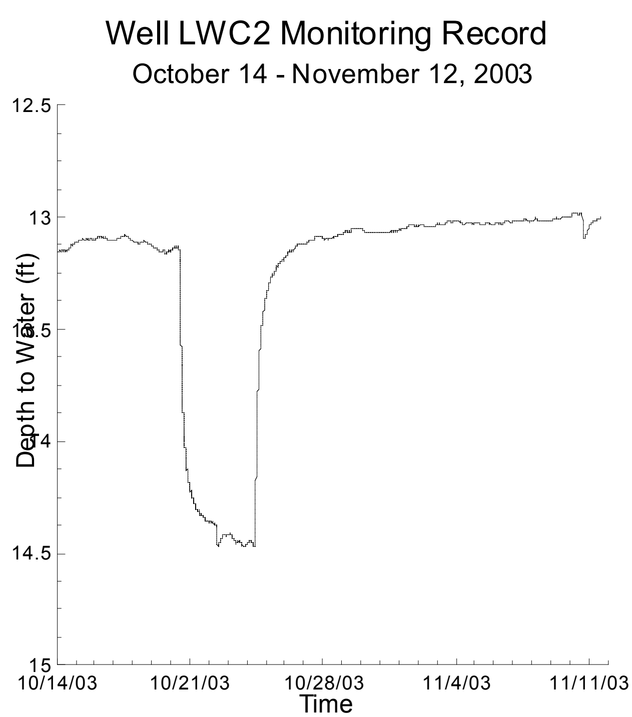


Figure 23 – Depth to water at well LWC2.

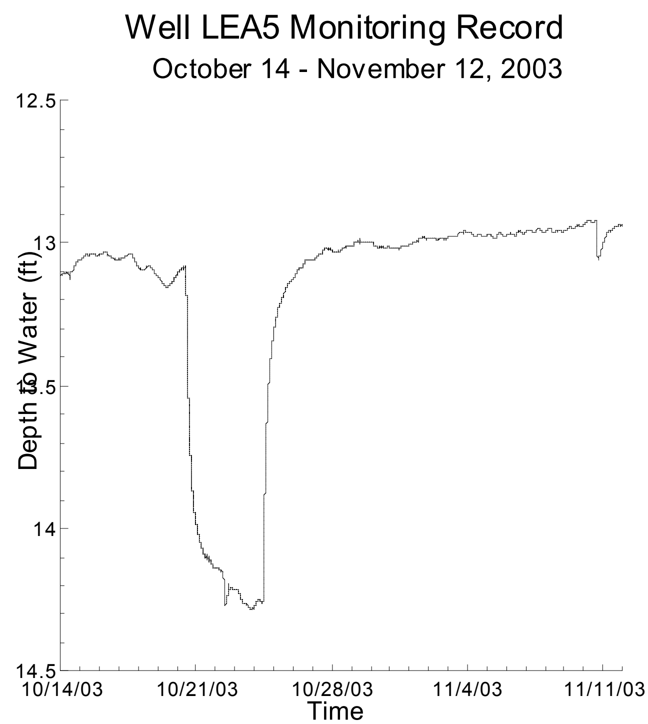


Figure 24 – Depth to water at well LEA5.

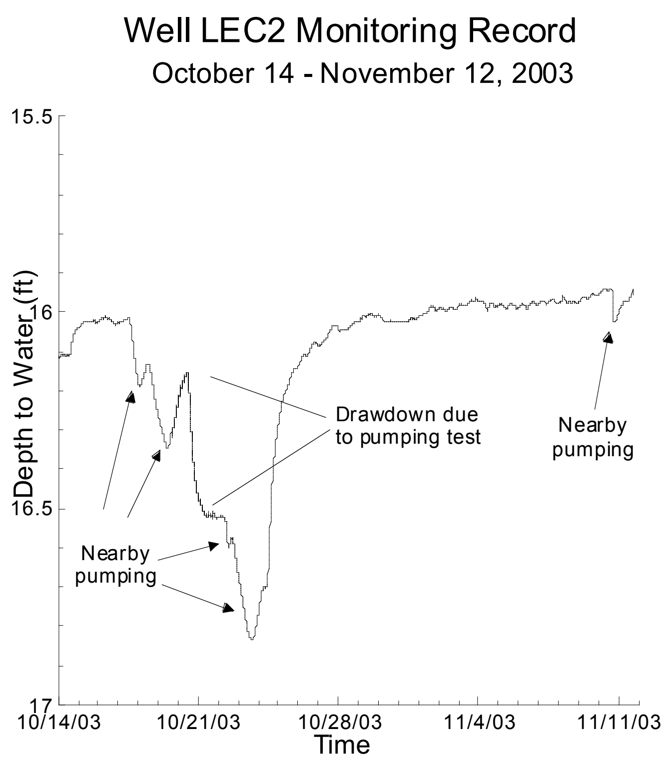


Figure 25 – Depth to water at well LEC2.

Monitoring Data – alluvial aquifer wells

Monitoring at well PT1b began at 10:45 AM on October 16, 2003 and concluded at 12:15 PM on November 11, 2003 (Figure 26). However, no data could be used beyond November 6 because of datalogger malfunctioning (see discussion of well PT1a data). A definite decline in water level could be observed in the monitoring data prior to the test. However, the electrical noise that appeared to begin shortly after the pump was cut off made it difficult to relate the pre- and post-pumping trends.

Monitoring at well PT2 began at 8:30 AM on October 16, 2003 and concluded at 11:22 AM on November 11, 2003 (Figure 27). A definite linear decline in water level can be observed prior to and immediately after the pumping test. A deviation from that trend is observed during the period of the pumping test. In late October, the water levels deviated from this trend as a result of nearby pumping activity.

Monitoring at well PT4b began at 8:45 AM on October 16, 2003 and concluded at 2:27 PM on November 11, 2003 (Figure 28). A definite linear decline in water level can be observed through the period during which the pumping test occurred, but the impact of the pumping is difficult to discern. In late October, the water levels deviated from this trend as a result of nearby pumping activity in a manner similar to that observed at well PT2.

Monitoring at well PT5b began at 6:30 PM on October 15, 2003 and concluded at 12:15 PM on November 11, 2003 (Figure 29). Electrical noise began to impact the data shortly after the pump was cut off on October 24. No data were available from 5:30 PM on October 30 until 11:15 AM on November 6. The noise in the transducer readings and the missing data are thought to have been caused by datalogger malfunctioning (see discussion of well PT5a data).

Monitoring at well PT7 began at 9:30 AM on October 16, 2003 and concluded at 1:45 PM on October 29, 2003 (Figure 30). Monitoring was concluded at that time because cattle were released into the pasture in which well PT7 was located. A definite decline in water level could be observed in the monitoring data prior to the test. An apparent shift in the position of the transducer at approximately 4:00 PM on October 21 made it difficult to relate the pre- and post-pumping trends. The cause of that shift could not be determined.

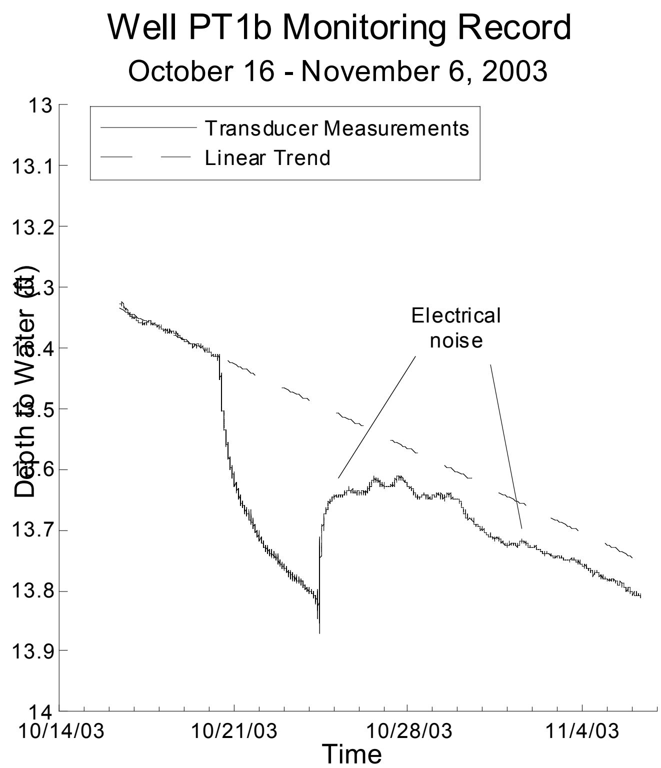


Figure 26 – Depth to water at well PT1b.

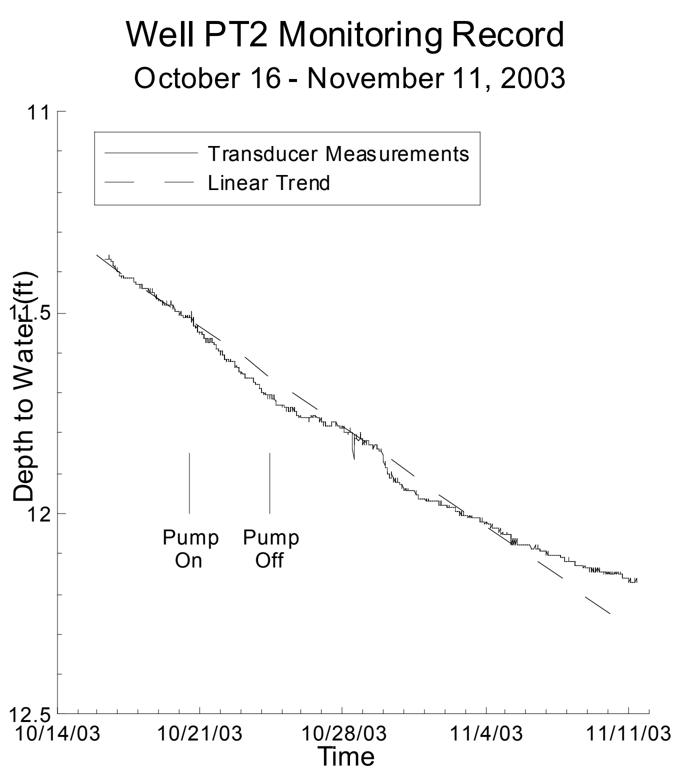


Figure 27 – Depth to water at PT2.

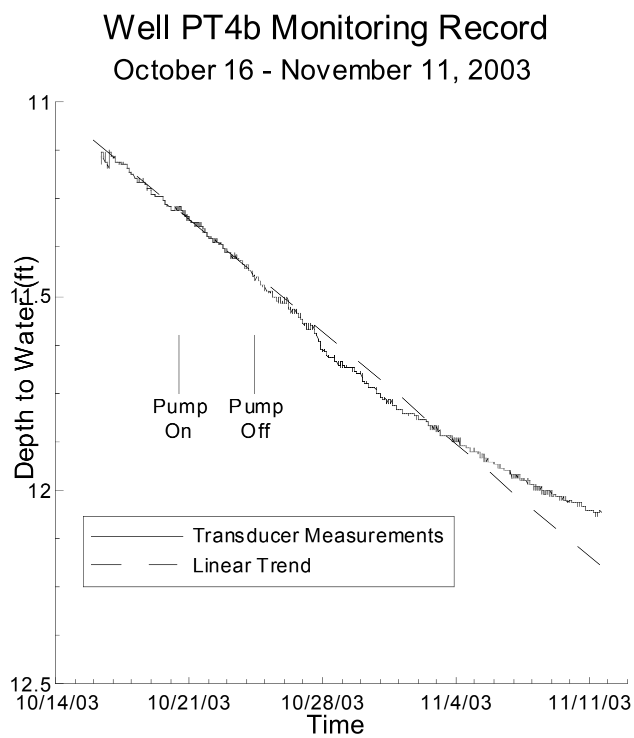


Figure 28 – Depth to water at well PT4b.

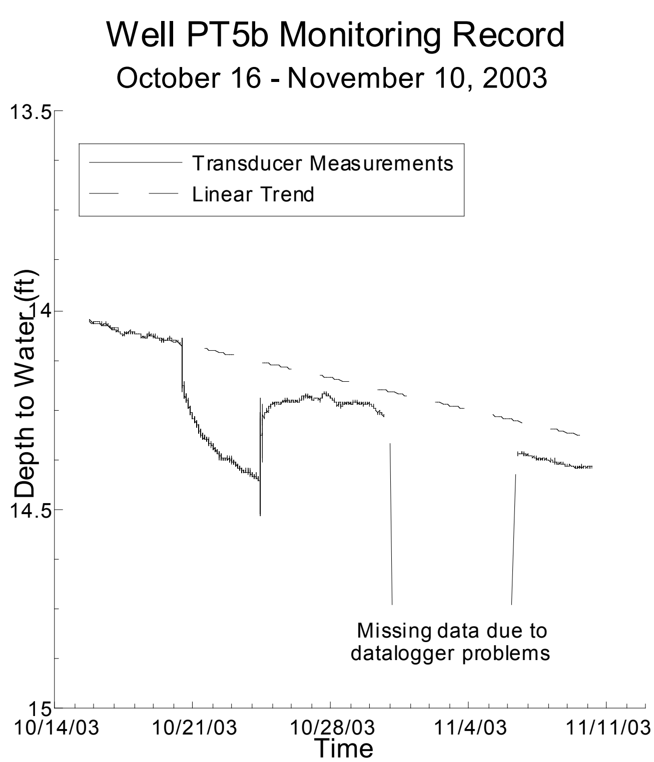


Figure 29 – Depth to water at well PT5b.

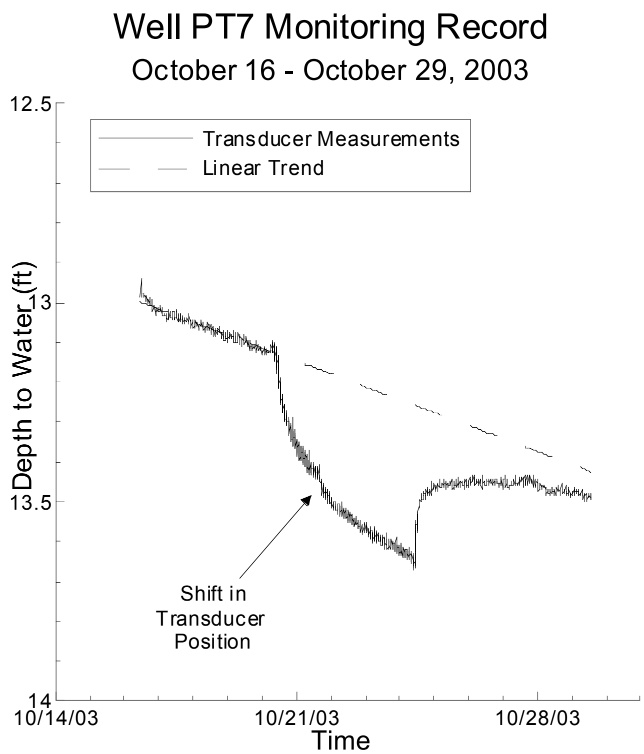


Figure 30 – Depth to water at well PT7.

Drawdown Analysis – High Plains aquifer wells

Wells PT3 and PT4a were chosen as the primary wells for use in the analysis because the drawdown at those wells was large compared to temporal trends and measurement noise, and those wells were less affected by early-time rate variations than wells closer to the pumping well. Wells PT1a and LWC2 were used to check the viability of the parameter estimates determined from wells PT3 and PT4a. Well PT5a was not used because of the poor performance of the transducer at that well (Table 4) and the electrical noise in the recovery period. Well PT6 was not used because of the difficulty in accounting for the rise in water level, while wells LEA5 and LEC2 were not used because of the difficulty in accounting for the impact of nearby pumping activity.

The Moench (1985) model for pumping tests in leaky confined aquifers was chosen for the analysis of the drawdown data because the drawdown data at all of the High Plains aquifer wells clearly show the impact of leakage. The Moench model is an extension of the model of Hantush (1960) that incorporates wellbore storage at the pumping well and skin effects. The implementation of the Moench model in AQTESOLV was used here.

The analysis of the PT3 data produced a very good fit to the drawdown data (Figure 31) for a transmissivity (T) of 5200 ft^2/day, a storage coefficient (S) of 1.3×10^{-4}, and a vertical hydraulic conductivity of the confining layer (K') of 6.8×10^{-3} ft/day. The cause of the difference between the measured drawdown and the model in the later portions of the recovery could not be determined. However, nearby pumping activity is the most likely explanation. The significant role of leakage during the test made it impossible to check the T estimate using the Theis recovery method as was done with the S2002 test. Note that the K' value is based on an average thickness for the confining layer of 17.1 ft (average of all wells in Table 2 except LEA5 and LEC2).

The analysis of the PT4a data produced a very good fit to the drawdown data (Figure 32) for a T of 5670 ft^2/day, a S of $2.1x10^{-4}$, and a K' of $7.2x10^{-3}$ ft/day. The difference between the measured drawdown and the Moench model in the later portions of the recovery period is again most likely a product of nearby pumping activity.

The agreement between the parameter estimates obtained from the analysis of drawdown data from wells PT3 and PT4a is quite good, so the averages of these values would appear to be reasonable estimates of the hydraulic properties of the High Plains aquifer and confining layer in the vicinity of pumping well IW. Those averages are 5440 ft^2/day (T), $1.7x10^{-4}$ (S), and $7.0x10^{-3}$ ft/day (K'). The average thickness of the High Plains aquifer in the vicinity of well IW is 18.4 ft (average of all wells from Table 2 except LEA5 and LEC2), so the transmissivity estimate equates to a hydraulic conductivity value of 295 ft/day. The storage coefficient equates to a specific storage value of $9.2x10^{-6}$ ft^{-1}. These estimates are both reasonable values for a coarse sand and gravel aquifer.

The viability of these estimates was assessed using drawdown from wells PT1a and LWC2. Type curves were generated using the average parameters determined from wells PT3 and PT4a and then compared to the drawdown data. The type curve for PT1a underpredicted the drawdown at that well (Figure 33). A good fit was obtained with the test data by decreasing the T to 4710 ft^2/day. Note that the variations in drawdown during the first 3000 seconds of the test are a product of the rate variations shown in Figure 17, which are largely damped out at the more distant observation wells.

The type curve for LWC2 was lagged in response to the drawdown data at early times but produced a reasonable match at later times until nearby pumping activity began to impact the test data (Figure 34). A closer match was obtained with the test data by increasing the T to 6580 ft^2/day and decreasing K' to $5.9x10^{-3}$ ft/day. However, even in that case, nearby pumping activity impacted the match after approximately the first day of the test.

Given that the comparisons with the average parameters were not bad at wells PT1a and LWC2 and that the comparisons could be improved by adjusting parameter values by 20% or less, the average parameters obtained at wells PT3 and PT4a were considered reasonable estimates of the hydraulic parameters in the vicinity of well IW. Note that if individual T estimates are considered, there is an apparent increase in transmissivity with distance from well IW – well PT1a (4710 ft^2/day), well PT3 (5200 ft^2/day), PT4a (5670 ft^2/day), and LWC2 (6580 ft^2/day). Further work would be necessary to assess if that increase is a product of an increase in hydraulic conductivity or thickness of the High Plains aquifer, or due to some artifact of the analysis.

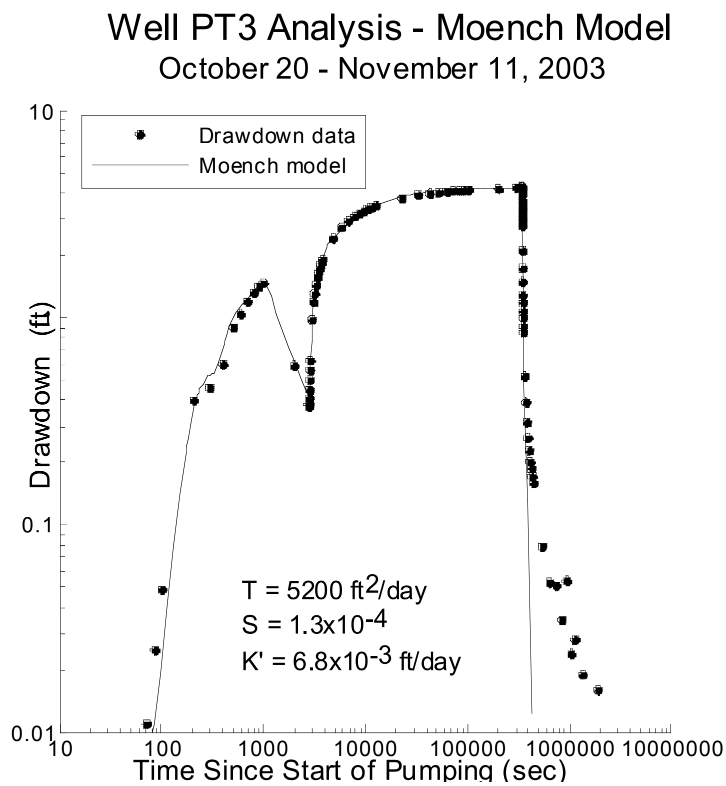


Figure 31 – Results of analysis of PT3 drawdown data with Moench model.

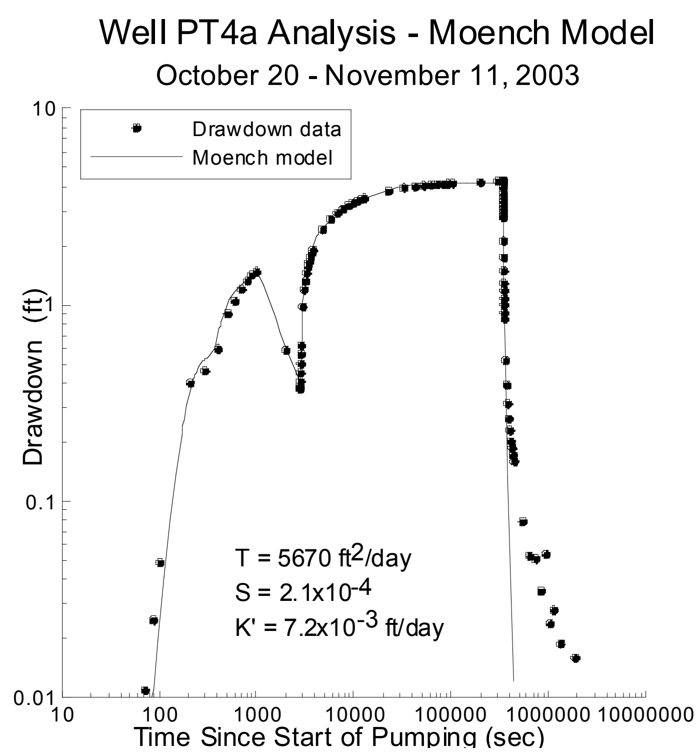


Figure 32 – Results of analysis of PT4a drawdown with Moench model

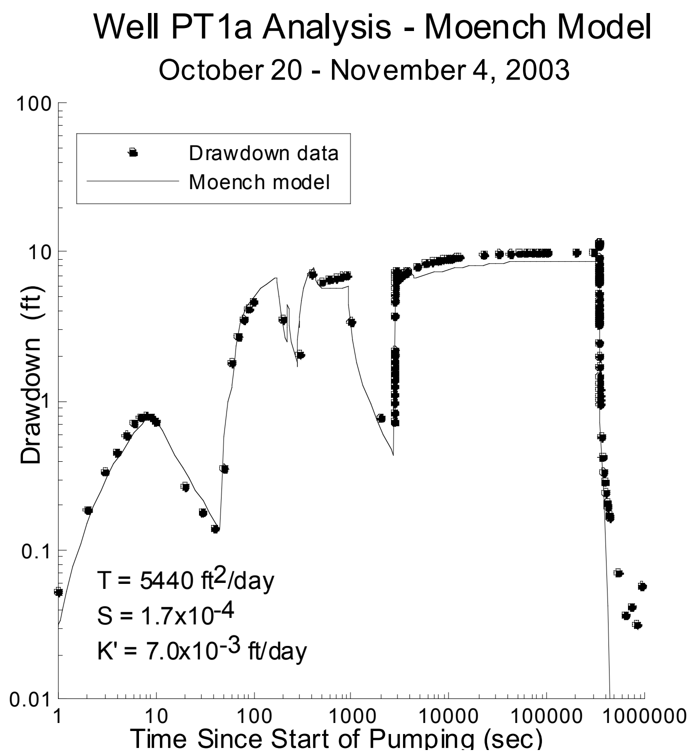


Figure 33 – Comparison of drawdown data from PT1a with type curve based on the average parameters from analysis of PT3 and PT4a.

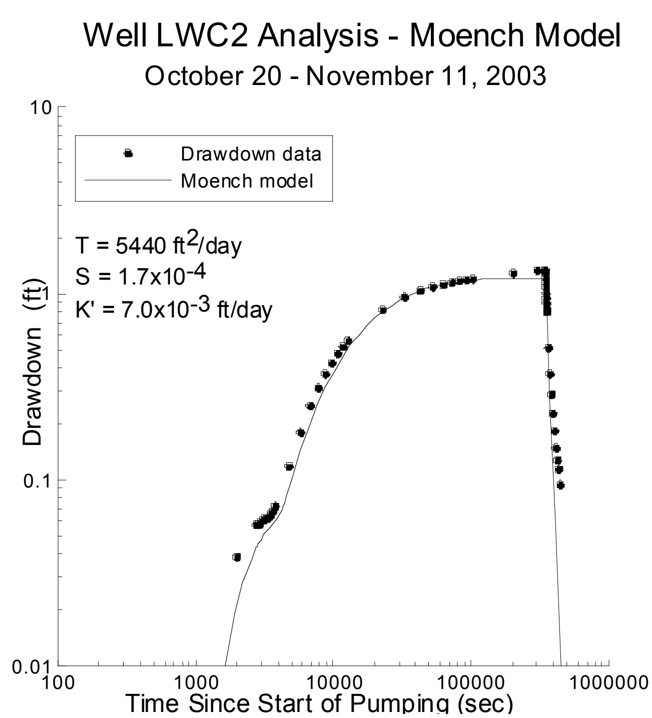


Figure 34 – Comparison of drawdown data from LWC2 with type curve based on the average parameters from analysis of PT3 and PT4a.

Drawdown Analysis – alluvial aquifer wells

The analysis of drawdown in the alluvial aquifer wells was difficult because of uncertainty regarding the magnitude of gravel-pack flow and the lack of an appropriate model to use for the analysis.

Flow down the gravel pack at well IW would produce a radial pattern of drawdown in the alluvial aquifer similar to what would be produced by pumping at a low rate in an unconfined aquifer. The magnitude of that flow is difficult to estimate, but, as is described in a later section, probably did not exceed 12 gpm (3.4% of total pumping). Assuming that the gravel pack flow is 3.4% of the pumping at all times during the test, an analysis of the drawdown at well PT7 with the Moench (1997) model for flow to a pumping well in an unconfined aquifer produced a transmissivity of 2900 ft^2/day and a specific yield of 0.07. A reasonable fit is obtained to about 100,000 seconds after which the drawdown is much greater than that predicted by the Moench model (Figure 35). That deviation is expected because of the increased drawdown required to meet the demands of pumping-induced leakage through the confining layer, a mechanism that is not incorporated in the Moench (1997) model. Despite the uncertainty about the flow rate, the results of this analysis indicate that flow down the gravel pack definitely occurred during the O2003 test. Note that the drawdown at well PT7 was computed as the deviation from the trend shown in Figure 30.

Currently, there is not an available analytical model that incorporates both gravel-pack flow and pumping-induced leakage to an underlying semiconfined aquifer. The development of such a model is one of the goals of an ongoing KGS research project on the impact of gravel-pack flow.

Summary

The results of the O2003 pumping test indicate that reasonable estimates for the transmissivity and storage coefficient of the High Plains aquifer in the vicinity of well IW are 5400 ft^2/day and 1.7×10^{-4}, respectively. Given an average thickness of 18.4 ft for the sands in the High Plains aquifer, these estimates correspond to hydraulic conductivity and specific storage values of 290 ft/day and 9.2×10^{-6} ft^{-1}, respectively. The test results also indicate that a reasonable estimate for the vertical hydraulic conductivity of the confining layer separating the High Plains aquifer from the alluvial aquifer is 7.0×10^{-3} ft/day. All of the parameter estimates appear consistent with the composition of the aquifer and confining layer.

The results of the O2003 pumping test also clearly indicate that vertical leakage from the alluvial aquifer is an important mechanism during pumping in the High Plains aquifer. Thus, pumping in the High Plains aquifer will eventually impact flow in the river. However, the time at which that impact occurs will dramatically lag that of the pumping because of the time needed for the vertical propagation of the pressure disturbance through the confining layer and then the lateral propagation of the disturbance in the alluvial aquifer.

The major uncertainty regarding the O2003 pumping test is the role of gravel-pack flow. Based on the drawdown data in the alluvial aquifer discussed in this section and an analysis of the geochemical data discussed in a later section, it is apparent that gravel-pack flow occurred during the pumping test. This flow was not great enough to have a major impact on the analysis of drawdown in the High Plains aquifer wells. However, gravel-pack flow should decrease the lag between pumping in the High-Plains aquifer and its impact on flow in the Arkansas River. It should also increase the magnitude of that impact. Further work is clearly needed to assess the impact of gravel-pack flow under both pumping and non-pumping conditions. Ongoing research at the KGS is addressing that issue.

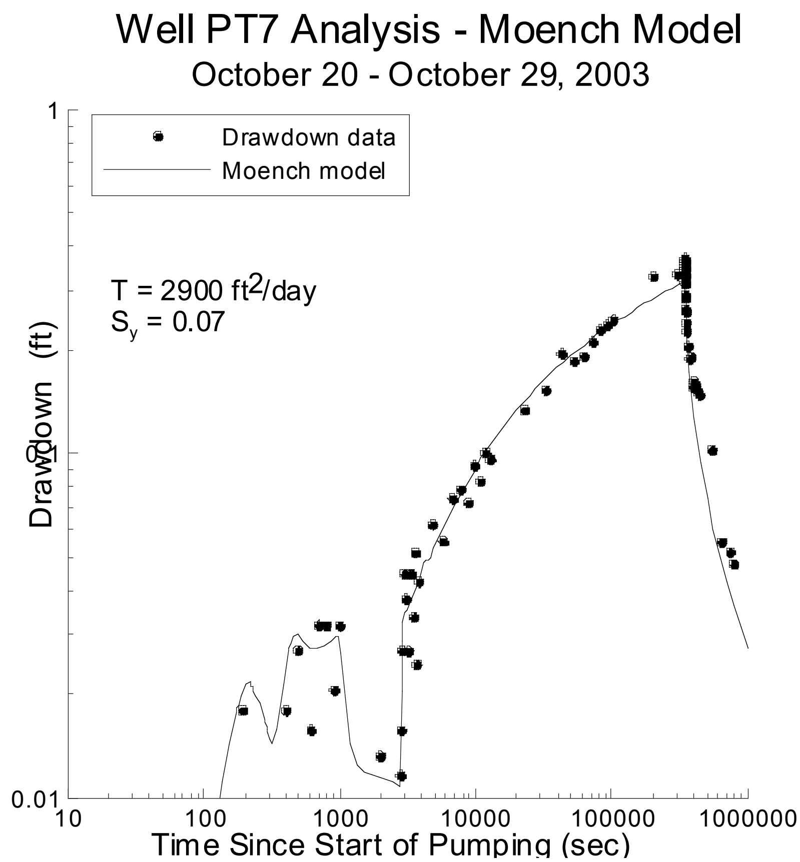


Figure 35 – Results of analysis of PT7 drawdown data with Moench (1997) model for flow to a pumping well in an unconfined aquifer

WATER SAMPLING AND ANALYSIS PROCEDURES AND RESULTS

The objective of the water-quality investigations was to determine changes in the chemistry of the pumped water and evaluate their relationships to the groundwater and river-water chemistry as another approach to assessing the impact of pumping on Arkansas River flow near Larned.

Procedures

Water samples were periodically collected from the pumping well during both pumping tests (Tables 7 and 8). Temperature and specific conductance were monitored in the field for the S2002 test, and conductance was recorded in the field during the first day of the O2003 test. The co-author of this report who prepared this section was stationed at the center pivot to record flowmeter readings during the first few hours of the O2003 pumping test. The center pivot is located 1584 ft from the irrigation well, so the temperature of the water at the center pivot did not reflect the temperature of the aquifer ground water and thus was not recorded. Water samples were also collected three months after the O2003 pumping test from two pairs of shallow and deep observation wells (sites PT1 and PT5) located near the irrigation well (Table 9). Profiles of specific conductance were recorded in observation wells PT1a, PT1b, and PT5b in November 2003, and in PT1b, PT2, PT3, PT4a and 4b, and PT5b in February 2003. Table 10 is a summary of the conductance values calculated or estimated as the mean for the screened interval of the observation wells.

Polyethylene bottles were filled with water samples and placed in a cooler with ice for transport to the analytical laboratories of the Kansas Geological Survey, where they were transferred to a refrigerator until analysis. The concentrations of silica, cations, and boron were determined using inductively-coupled plasma spectrophotometry. Alkalinity was measured by automated titrimetry and converted to bicarbonate content. Sulfate, chloride, nitrate, and bromide concentrations were determined using colorimetric or ultraviolet spectrophotometry on automated flow-injection or segmented-flow instruments. The chemical data for the water samples for the pumping tests and associated observation wells are listed in Tables 7-9. Water-quality data obtained from sampling of selected observation wells for studies of stream-aquifer interactions and phreatophyte water consumption at the O'Rourke Bridge site were used in interpretation of the data from both pumping tests.

Results and Discussion

September 2002 (S2002) pumping test

The temperature of the water pumped from well LEA2 increased 0.5 °C during the first 200 minutes of the pumping test and then rose slowly another 0.7 °C during the rest of the test (Table 7, Figure 36). Except for a small decrease during the first 15 minutes of pumping, the specific conductance remained constant during the test. Sulfate and chloride concentrations varied by 17 mg/L and 3.8 mg/L during the first hour of pumping, increased by a small amount during the next 10 hours, decreased slowly during the next 15 hours, and became relatively constant the rest of the test (Table 7, Figure 36). The estimated analytical precision of

Table 7. Sample collection information, field data, and laboratory chemical data for water pumped from well LEA2 during the S2002 pumping test. The units of specific conductance (Sp.C.) in µS/cm are equivalent to µmho/cm. The total dissolved solids concentration (TDS) is calculated as the sum of dissolved constituents (where bicarbonate is multiplied by 0.4917).

Date	Time	Pumping time min.	Water temp. deg. C	Air temp. deg. C	Field Sp.C. µS/cm	Lab Sp.C. µS/cm	Lab pH	SiO_2 mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	HCO_3 mg/L	SO_4 mg/L	Cl mg/L	F mg/L	NO_3-N mg/L	Br mg/L	B mg/L	TDS mg/L
9/17/02	8:42	1			1322	1320								309	80.4		3.52	0.179		
9/17/02	8:49	8			1305	1300								309	76.9		3.37	0.180		
9/17/02	8:56	15				1310	7.60	20.7	125	35.2	113	7.8	298	312	77.7	0.65	3.41	0.180	0.15	840
9/17/02	8:57	16			1314															
9/17/02	9:07	26	16.8																	
9/17/02	9:11	30			1320	1320								329	80.7		3.43	0.183		
9/17/02	9:41	60			1321	1320								326	79.9		3.46	0.182		
9/17/02	9:48	67	17.0	21.5																
9/17/02	10:02	81			1322															
9/17/02	10:41	120			1330	1320								327	79.6		3.48	0.185		
9/17/02	11:11	150			1330															
9/17/02	11:54	193			1329															
9/17/02	12:04	203	17.3	30.1																
9/17/02	12:41	240			1330	1320								329	79.9		3.70	0.184		
9/17/02	14:09	328			1337															
9/17/02	14:16	335	17.3	32.4																
9/17/02	14:42	361			1337	1320								335	80.0		3.93	0.185		
9/17/02	17:51	550				1325								326	80.3		4.16	0.186		
9/17/02	18:00	559	17.4	30.7																
9/18/02	2:09	1048			1326	1320								326	79.0		4.34	0.187		
9/18/02	2:20	1059	17.5	22.2																
9/18/02	8:41	1440	17.7	21.0	1330	1320	7.60	21.4	125	35.9	107	8.2	289	311	78.4	0.68	4.45	0.182	0.15	831
9/18/02	14:41	1800	17.9	28.7	1334	1320								312	78.5		4.54	0.181		
9/18/02	16:52	1931	17.9	22.0																
9/18/02	19:47	2106	17.9	22.0	1336	1320								306	78.7		4.65	0.183		
9/19/02	2:11	2490	17.9	17.5	1342	1320								310	78.1		4.61	0.180		
9/19/02	10:20	2979	18.0	15.2																
9/19/02	10:41	3000			1346	1320	7.60	21.6	125	36.4	104	8.4	288	314	78.3	0.70	4.79	0.184	0.17	831

Table 8. Sample collection information, field data, and laboratory chemical data for water pumped from well IW during the O2003 pumping test. See Table 7 above for explanation of Sp.C. and TDS.

Sample date	Sample time	Pumping time min.	Field Sp.C. µS/cm	Lab Sp.C. µS/cm	Lab pH	SiO_2 mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	HCO_3 mg/L	SO_4 mg/L	Cl mg/L	F mg/L	NO_3-N mg/L	Br mg/L	B mg/L	TDS mg/L
10/20/03	11:30	-35	1360	1335	7.45	18.6	157	31.7	100	5.4	273	395	57.4	0.53	2.15	0.232	0.129	911
10/20/03	12:10	5	1700	1670	7.40	19.4	186	36.9	154	6.3	295	545	81.3	0.65	2.53	0.272	0.176	1187
10/20/03	12:20	15	1704	1690								539	81.8		2.39			
10/20/03	12:50	45	1637	1610	7.40	19.7	184	36.6	142	6.0	291	530	74.0	0.58	2.19	0.266	0.150	1147
10/20/03	13:15	70	1565	1550	7.40	19.4	179	35.6	130	5.7	287	513	71.0	0.54	2.10	0.256	0.135	1106
10/20/03	14:30	145	1472	1450								464	64.0		1.90			
10/20/03	16:53	288	1377	1360	7.40	18.4	159	31.6	101	5.2	275	426	58.9	0.51	1.94	0.235	0.111	946
10/21/03	8:34	1229	1383	1360	7.60	18.7	163	32.7	103	4.8	275	420	58.6	0.50	2.03	0.233	0.104	947
10/21/03	19:07	1862		1360								427	58.5		2.12			
10/22/03	9:49	2744		1375	7.45	19.0	164	32.5	104	5.2	276	426	59.6	0.49	2.10	0.239	0.108	957
10/22/03	18:55	3290		1375								427	58.9		2.10			
10/23/03	8:51	4126		1380								428	59.2		2.10			
10/23/03	18:40	4715		1385								430	59.5		2.17			
10/24/03	10:18	5653		1390	7.40	19.0	165	32.7	105	5.2	278	444	59.2	0.49	2.17	0.243	0.122	978

Table 9. Sample collection information, field data, and laboratory chemical data for water pumped from wells used as observation wells in the O2003 pumping test. See Figure 1b for an areal view of observation well network. See Table 7 above for explanation of Sp.C. and TDS. See Table 10 for well depth and screened interval information.

Well No.	Sample date	Sample time	Field Sp.C. µS/cm	Lab Sp.C. µS/cm	Lab pH	SiO_2 mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	HCO_3 mg/L	SO_4 mg/L	Cl mg/L	F mg/L	NO_3-N mg/L	Br mg/L	B mg/L	TDS mg/L
PT1a	1/24/04	11:54	1475	1460								473	56.8		1.2			
PT1a	1/24/04	12:13	1466	1450	7.80	19.1	180	36.1	93.9	4.3	267	462	56.0	0.48	1.2	0.263	0.103	983
PT1b	1/24/04	12:57	1874	1850								609	95.8		2.1			
PT1b	1/24/04	13:12	1874	1850	8.10	19.4	193	40.3	181	7.2	302	605	95.1	0.71	2.2	0.287	0.229	1290
PT5a	1/24/04	10:00	1159	1140								249	59.1		3.6			
PT5a	1/24/04	10:15	1158	1140	8.00	17.5	122	24.6	88.0	4.9	274	266	59.1	0.52	3.6	0.172	0.107	717
PT5b	1/24/04	10:57	2020	1950								668	101		1.9			

PT5b	1/24/04	11:02	2020	1960	8.05	18.8	214	42.4	192	7.2	323	668	100	0.74	1.9	0.313	0.227	1402

Table 10. Specific conductance of ground water in the screened interval of the observation wells installed for the O2003 pumping test.

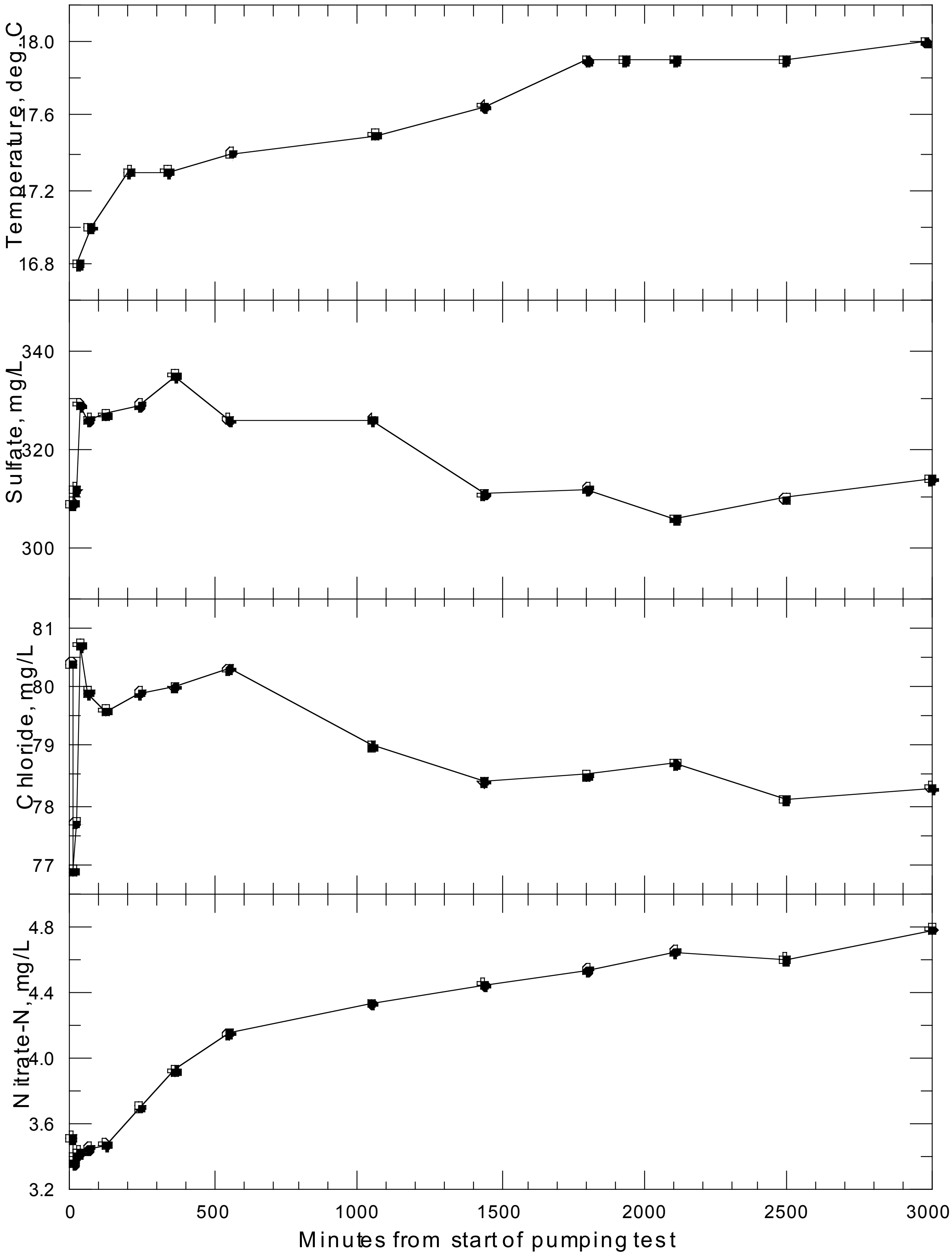
			Measured or estimated mean Sp.C., µS/cm, In screened interval		
Well	Well depth, ft bls*	Screened interval, ft bls	Field value from conductance profile 11/12/2003	Lab value for pumped sample 1/24/04	Field value from conductance profile 2/25/04
Alluvial aquifer					
PT1b	28.1	12.9-22.7	1801	1850	1799
PT2	24.4	14.1-24.0			1759
PT4b	25.1	14.9-24.7			958
PT5b	29.8	19.6-29.4	1923	1960	2080
High Plains aquifer					
PT1a	67.1	61.9-66.7	1595	1450	
PT3	67.1	61.9-66.7			2130
PT4a	67.1	61.9-66.7			2130
PT5a	66.3	61.1-65.9		1140	

* Feet below land surface

the sulfate and chloride determinations is about 1% of the sulfate values (~3 mg/L) and approximately 0.5% for the chloride values (~0.4 mg/L). Thus, the very small changes in concentration during the second half of the test could be largely due to analytical error. After a very small decrease during the 8 minutes of pumping, the nitrate concentration increased during the rest of the test (Table 7, Figure 36). The estimated precision in the nitrate concentration is about 0.05 mg/L. Therefore, the greater rate of increase in nitrate content during the first 10 hours of pumping compared to the rest of the test is analytically verifiable.

Temperature measured in and chemical data for water samples collected from monitoring wells at the O'Rourke Bridge site within a year following the S2002 pumping test help in interpreting the changes observed during that test. The data indicate that the primary cause for the temperature and chemical changes is water drawn in laterally from under the river channel to the west of well LEA2 and not water flowing vertically from below the screened interval of the well. The temperature and water chemistry of the ground waters at the location of well LEA2 changes both vertically within the entire alluvial aquifer and laterally within the aquifer towards the river. As the well was pumped during the test, the lateral radius within which ground water was captured in the most permeable strata grew to include the area near and just under the river channel. A small clay layer at 17 ft bls (Figure 6) retarded the vertical movement of ground water from below the screen interval of LEA2 (11.4-16.1 ft bls).

A temperature profile measured at one-foot intervals in well LEA2 a year after (9/18/03) the S2002 test showed a temperature decrease with depth (from 20.0 to 18.7 °C) for the depth interval 8-17 ft bls. The decreasing temperature with depth represented the warming of the shallower water by summer temperatures. Therefore, the 1.2 °C warming of the water during the pumping test (Figure 36) cannot be explained by upconing of deeper aquifer water.



Temperature, deg. C
18.0
17.6
17.2
16.8
Sulfate, mg/L
340
320
300
Chloride, mg/L
81
80
79
78
77
Nitrate-N, mg/L
4.8
4.4
4.0
3.6
3.2
0
500
1000
1500
2000
2500
3000
Minutes from start of pumping test

Figure 36. Change in temperature and sulfate, chloride, and nitrate concentrations of the discharged water during the S2002 pumping test.

The static water level in well LEA2 just before the pumping test was about 10.1 ft bls. There was a pool of water in part of the river channel to the west of LEA2 during the pumping test that represented essentially the same elevation of the water-level surface. The ground water underlying the channel had about 8 ft less of overlying sediment than at well LEA2, allowing the transfer of warm, summer air temperature more rapidly into the water in the alluvial aquifer under the river channel than at well LEA2. Without flow in the river, the flow in the alluvial aquifer is driven in part by a hydraulic gradient component that crosses the river from west to east. Thus, a lateral temperature gradient of warmer to cooler water is expected to have been present in the shallow alluvial aquifer between the river channel and well LEA2.

The increase in nitrate concentration during the pumping test (Figure 36) fits a concentration gradient of larger values in the alluvial ground water under the river channel to smaller concentrations to the east at well LEA2. Monitoring wells installed for a study of phreatophyte water consumption are located from a few to several hundred feet to the southwest of LEA2 on the west side of the main river channel. This is the general direction from which ground water flows in the alluvial aquifer towards well LEA2 when there is no river flow. Sampling of the shallow phreatophyte wells on 4/30/03 indicated that there was a general decrease in nitrate-nitrogen concentration in the alluvial aquifer from 17.9 mg/L in ground water from the most southwestern well (LWPH6) to 9.0 mg/L for the most eastern well (LWPH1) located on a sand bar on the west side of the main flow channel. Fertilized fields that could be the source of the nitrate content in the alluvial ground water exist just to the west of the riparian area on the west side of the river. The fields just to the east of the LEA2 location are pastures. A water sample collected on 5/1/03 from an observation well (LEC3) screened within the shallow alluvial aquifer 892 ft east of well LEA2 contained 2.4 mg/L nitrate-nitrogen. Part of the decreasing concentration gradient of nitrate from the river to LEC3 could be due to the alluvial aquifer recharge from a large flow event in the Arkansas River in September 2001. The source of the flow was fresh runoff from the Pawnee River basin; the high flow sampled at the Larned gaging station on 9/19/01 contained 0.9 mg/L nitrate-nitrogen and low dissolved solids concentrations. However, remnants of this recharge are not believed to be the main reason for a nitrate gradient from the river to well LEA2 at the time of the pumping test because the sulfate and chloride concentrations would have also been expected to have increased during the pumping test, reflecting a higher sulfate content in the groundwater from under the phreatophyte wells in comparison with the September 2001 river recharge. The nitrate concentration increased during the pumping test by 40% from the value 15 minutes after the start of pumping to the end of the test, whereas the sulfate and chloride contents of water pumped at 15 minutes and the test end each differed by less than 1%.

October 2003 (O2003) pumping test

A water sample was collected 8 minutes after the pump at well IW was turned on to fill the piping system, about 35 minutes before the start of the main pumping period. The specific conductance, total dissolved solids (TDS) content, and the concentrations of all the major and minor dissolved constituents increased substantially from this pre-test sample to a sample collected 5 minutes after the beginning of the main period of pumping (Table 8, Figures 37 and 38). The specific conductance and the dissolved constituent concentrations then decreased until either reaching a minimum value somewhere between 5 to 21 hours after the start of the

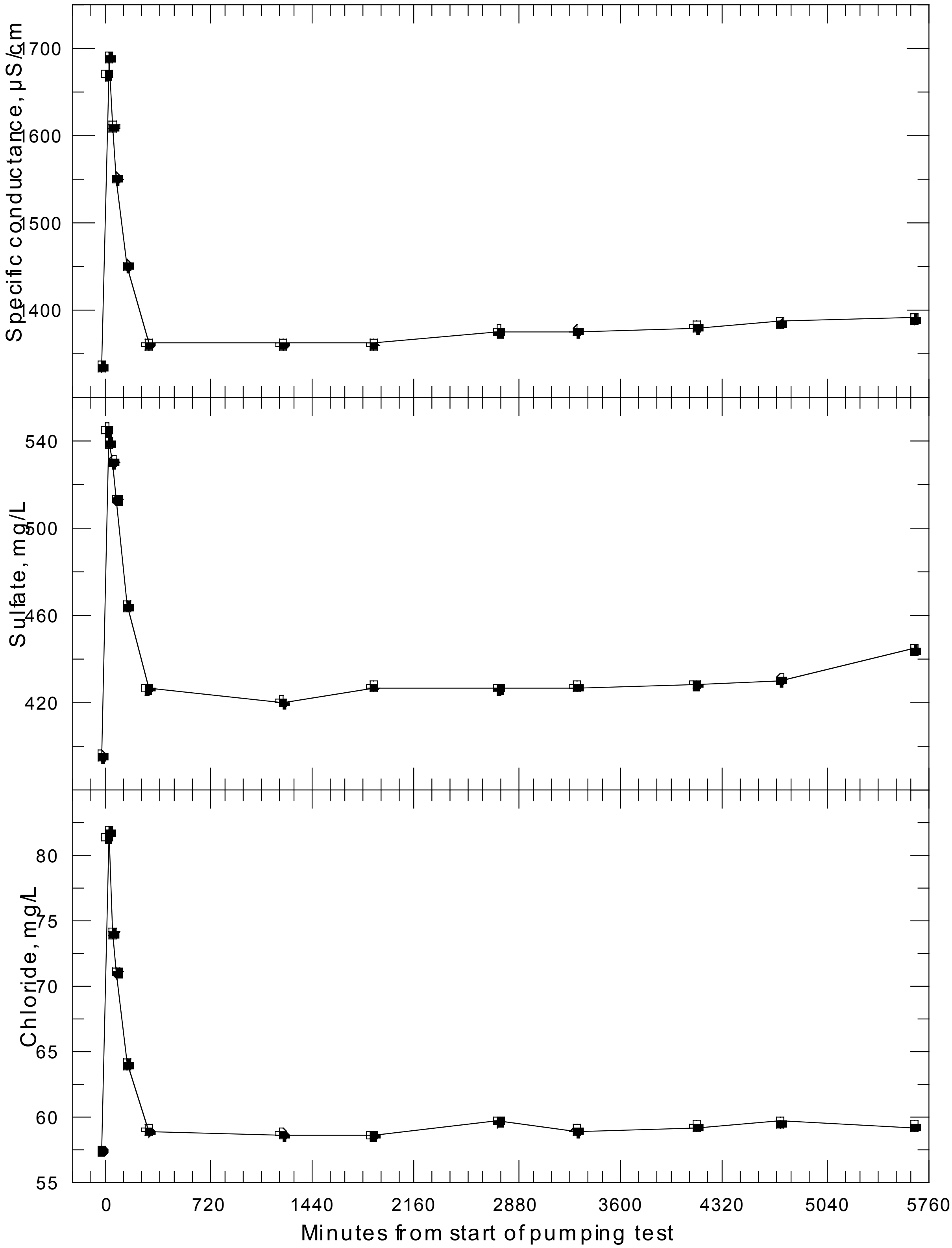


Figure 37. Change in specific conductance and sulfate and chloride concentrations of the discharged water during the O2003 pumping test.

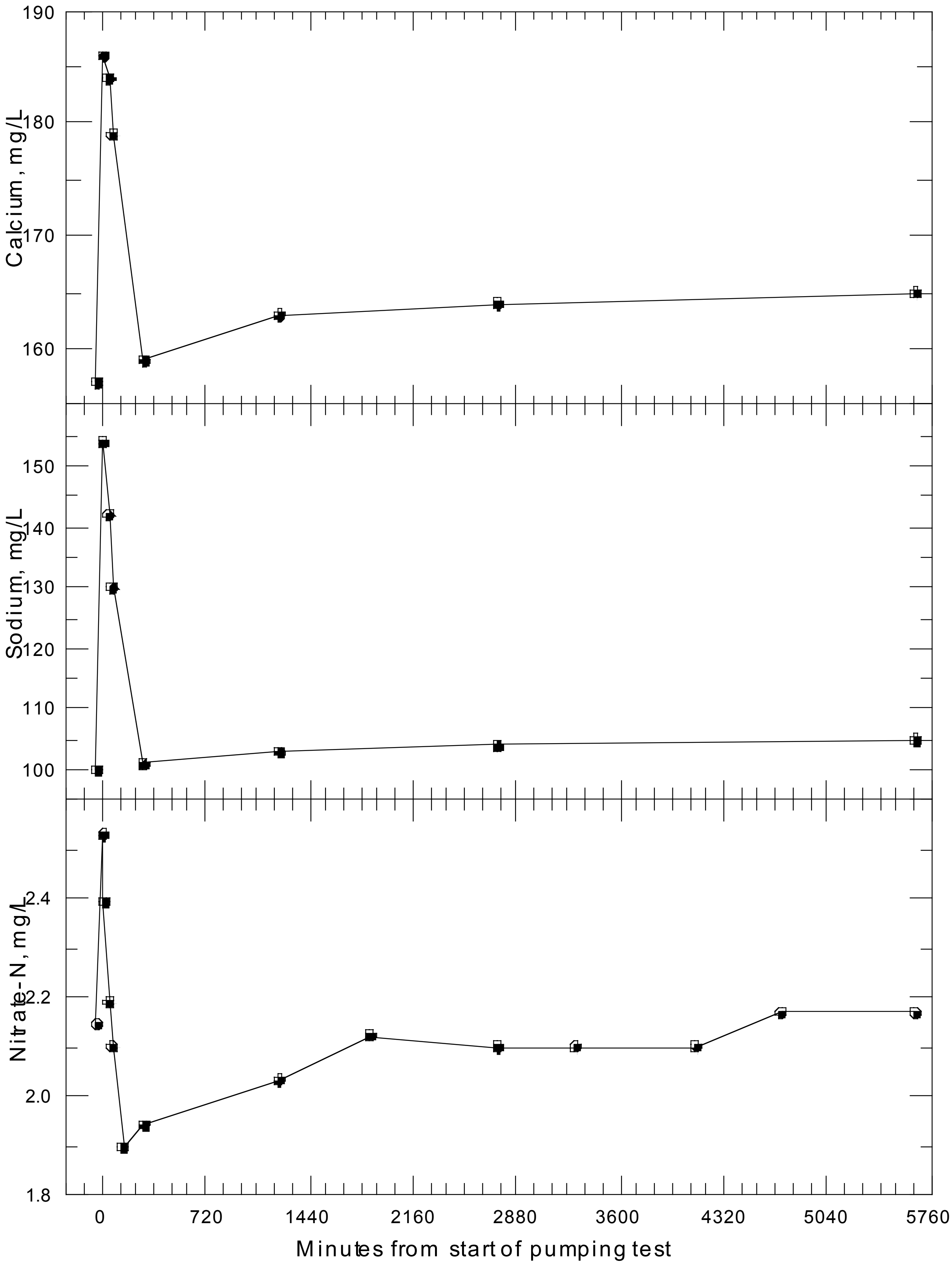


Figure 38. Change in calcium, sodium, and nitrate concentrations of the discharged water during the O2003 pumping test.

the main period of pumping or stabilizing during the rest of the test (Table 8, Figures 37 and 38). Except for sulfate, the minimum values of all major constituent concentrations and the specific conductance in the samples collected from 288 to 1229 minutes (4.8-20.5 hours) after the start of the main pumping period differed from the pre-test sample by only about 2% or less. The minimum values for the TDS and sulfate concentrations in the 4.8 to 20.5 hour samples were approximately 4% and 6% greater than in the pre-test sample, whereas the minimum value for nitrate was about 12% lower than in the pre-test sample. The minimum for nitrate was reached after 145 minutes (2.4 hours) of pumping. After a day of pumping, the specific conductance, TDS, and concentrations of nearly all dissolved constituents increased slightly until the end of the test. The values for specific conductance and the concentrations of TDS and all measured dissolved constituents except sulfate differed by less than 8% between the pre-test and test-end samples. The sulfate content in the last sample was about 12% greater than in the pre-test water.

The chemical relationships for waters in the alluvial and High Plains aquifers and past Arkansas River flow in the study area provide insights into the origin of constituents and changes in the water pumped during the test. The arrows on the lines connecting the filled circles for the O2003 pumping test on Figures 39 and 40 indicate the progression of the chemical changes during the test period. Larger filled circles in the figures represent chemical data for samples from the High Plains aquifer collected from two observation wells (PT1a and PT5a) in the nests installed nearest well IW for the pumping test, and from observation wells LWC2 and LWPH4c installed for stream-aquifer and phreatophyte studies, respectively. Unfilled circles in Figures 39 and 40 represent chemical data for samples from the alluvial aquifer collected from four observation wells (PT1b, PT5b, LWC1 and LWPH4b) next to the observation wells in the High Plains aquifer. The thin lines connecting points for Arkansas River water collected either at Larned or the Larned gaging station during the past decade enclose the ranges in dissolved constituent concentrations for the river.

The points for well nests PT1 and PT5 on Figures 39 and 40 represent samples collected from the wells three months after the O2003 pumping test. Table 10 compares the specific conductance of these samples with field values from conductance profiles measured in some of the wells before and after the sampling, along with profiles for other observation wells installed for the O2003 test. The conductance profiles for the wells installed in the High Plains aquifer did not reach the screened interval because the probe cable is only 50 ft long. In addition, surface tension on the probe cable from the wet PVC surface in the small diameter (1.0-inch diameter) wells prevented the probe from sinking further than 44-46 ft below the top of the well casing. Even though the conductance profile did not reach the screened interval, the relatively constant conductance measured in the profile and the fact that the wells had been developed indicate that the water in the column was representative of water that had been produced from the aquifer. Table 10 indicates that the water in the High Plains aquifer at well PT1a was somewhat less saline three months after the pumping test in comparison with one month after the test. The conductance of ground water in the alluvial aquifer at well PT1b remained relatively constant from one to 4 months after the pumping test, whereas the salinity of ground water at well PT5b increased a small amount.

The specific conductance and concentration of TDS and nearly all dissolved constituents in the samples collected just prior to and at the end of the pumping test were between the values

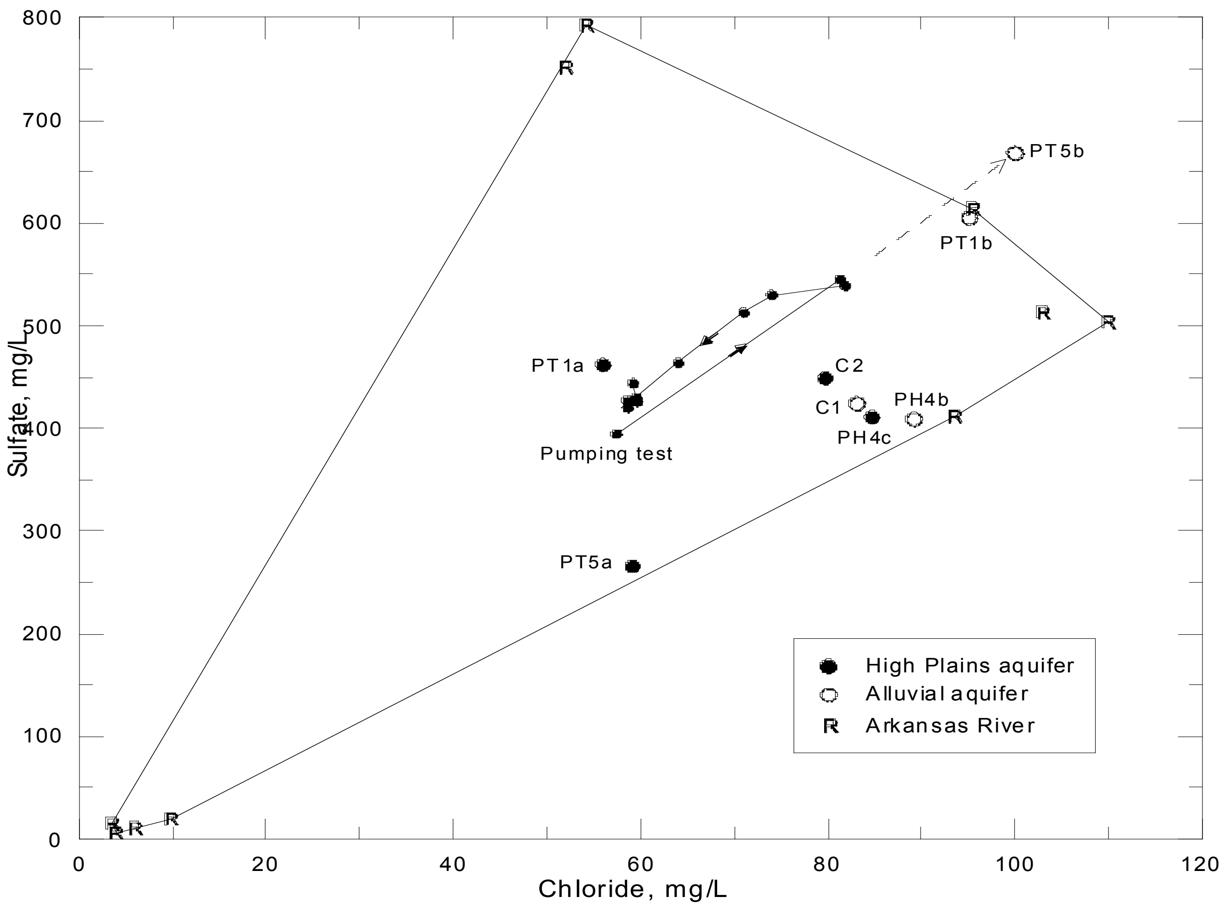


Figure 39. Sulfate versus chloride concentration in water samples from the discharge water of the O2003 pumping test and from observation wells screened in the alluvial and High Plains aquifers near and in the general area of well IW. The designations for the LW wells have been shortened to facilitate labeling on the figure (C1 = LWC1, C2 = LWC2, PH4b = LWPH4b, PH4c = LWPH4c).

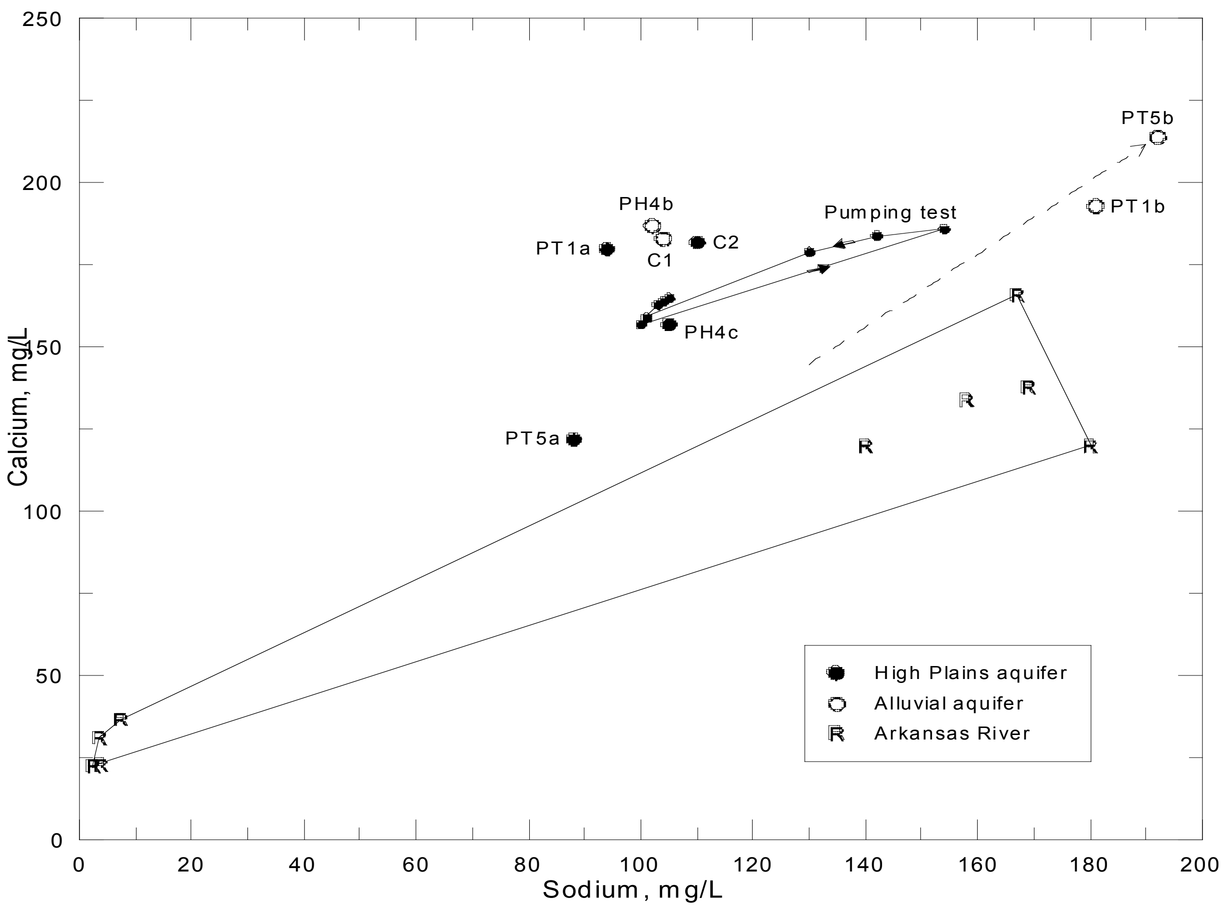


Figure 40. Calcium versus sodium concentration in water samples from the discharge water of the O2003 pumping test and from observation wells screened in the alluvial and High Plains aquifers near and in the general area of well IW. The designations for the LW wells have been shortened to facilitate labeling on the figure (C1 = LWC1, C2 = LWC2, PH4b = LWPH4b, PH4c = LWPH4c).

for samples collected from observation wells PT1a and PT5a (Tables 8 and 9, Figures 39 and 40). Thus, the average composition of the ground water in the High Plains aquifer surrounding well IW, but at a distance outside the radius of the impact of gravel-pack flow from the well since the last period of irrigation pumping, was generally between the compositions at wells PT1a and PT5a. The concentrations of sulfate, chloride, calcium, and sodium were substantially greater in the alluvial aquifer than in the pre-test sample from the irrigation well in the High Plains aquifer in contrast to generally similar concentrations for well sites LWC and LWPH4 (except for calcium at site LWPH4) (Figures 39 and 40).

The points for samples from wells PT1b and PT5b on Figure 39 either lie outside or at the edge of the enclosed range for points representing Arkansas River waters, whereas the points for the other well samples lie within the river chemistry boundaries. Evapotranspiration consumption of irrigation water withdrawn from the alluvial and High Plains aquifers hydraulically up-gradient from the site, followed by infiltration of the more concentrated water (containing the residual dissolved solids) to the water table and flow to well IW is believed to be the cause for the higher sulfate and chloride concentrations. The dashed line pointing to the symbol for well PT5b represents the direction in which the chemistry would change if conservative (without reaction) concentration of sulfate and chloride occurred due to consumption of water leaving dissolved constituents in the smaller volume of residual water. Figure 40 shows that the points for all the well waters lie above (at higher calcium concentration) the boundaries for the range in river composition. The source of much of the additional calcium could be weathering and dissolution of minerals in the aquifer sediments, particularly calcite. In addition, the higher calcium content could partially reflect the composition of ground water flowing into the alluvium and the High Plains aquifer from the Cretaceous bedrock to the west. Except for waters from wells PT1b and PT5b, the sodium concentration of the ground waters represented in Figure 40 lie within the range for the river water. The evapotranspiration concentration mechanism also fits as an explanation for the higher calcium and sodium concentrations in the water from wells PT1b and PT5b in comparison with the other ground waters in the area. The dashed line pointing to the symbol for well PT5b in Figure 40 represents the evapotranspiration concentration change in a similar manner as it does in Figure 39.

The spike in the constituent concentrations after the start of the pumping test (Figures 37 and 38) is consistent with the withdrawal of High Plains aquifer water in which was mixed some alluvial aquifer water. The water-level declines described earlier in this report for the pumping test indicate that well IW is screened in the High Plains aquifer. The water-quality data also support this because, if the screened interval of the well included part of the alluvial aquifer, the large concentration spike at the start of the pumping test would not be expected because there would be a consistent mix of alluvial and High Plains aquifer waters. Leakage of alluvial aquifer water through the low-permeability confining layer to the underlying High Plains aquifer, both during periods of pumping and no pumping, is expected to occur across the study area and therefore would not be a cause for the substantial changes in water quality in the first few hours of the test. The concentration spike can best be explained by the movement of alluvial aquifer water down the gravel pack in the annular space between the casing and borehole of well IW. There was a static head gradient of approximately 1.6-1.9 ft between the alluvial aquifer and the High Plains aquifer based on water-level measurements obtained during three different days within the week prior to the pumping test from the pairs of observation wells at sites PT1 and

PT5. The pre-test sample (-35 min in Table 8) represented water in the pipe extending 1584 ft from well IW to the center pivot that remained from the previous period the well was used for irrigation, and that was pushed to the center pivot during the short pre-test pumping. The well was last pumped for irrigation 12 days prior to the pumping test. Between that time and the start of the pumping test, water flowed slowly down the gravel pack from the alluvial aquifer into the upper portions of the High Plains aquifer. Whittemore and Butler described the mechanism of gravel pack flow associated with large-diameter wells as being potentially important for the movement of shallow, saline water into the High Plains aquifer along the upper Arkansas River corridor (Whittemore and Butler, 1997).

The mixing of different waters on Figures 39 and 40 can be represented by straight lines. Extension of the straight line, which indicates the substantial increase in dissolved constituent concentrations from the pre-test to the 5-minute pumping sample in Figures 39 and 40, to greater concentrations indicates that water similar to that in the alluvial aquifer in the area of the irrigation well (as represented by samples from observation wells PT1b and PT5b) is the most likely source of the concentration jump. This relationship supports the mixing of alluvial aquifer water with High Plains aquifer water through flow down the gravel pack of well IW. The alluvial aquifer water that reached the High Plains aquifer between the last period of irrigation pumping and the O2003 pumping test is expected to have been concentrated in the area immediately around and down hydraulic gradient from the screen in well IW, and in the upper part of the High Plains aquifer. During the first five hours of pumping, most of the alluvial aquifer water that entered the High Plains aquifer via the gravel pack between the last period of irrigation pumping and the O2003 test was removed. The last time well IW was pumped was from 9:15 to 14:00 on October 8, 2003; the well was shut off when rain began that totaled 0.92 inch on that afternoon. The period of pumping, 4.75 hrs (285 min) was very close to the pumping-test time at which the concentration spike in Figures 37 and 38 ended (4.8 hrs or 288 min).

The gravel-pack flow during the period of no pumping between October 8 and October 20 can be estimated by determining the volume of alluvial aquifer water removed from the High Plains aquifer during the first few hours of the pumping test as indicated by the concentration peaks in Figures 37 and 38. Although gravel-pack flow prior to the October 8 pumping also entered the High Plains aquifer, the concentration spike during the first part of the pumping test is assumed to represent mainly the new flow into the aquifer since the end of the last pumping period. The flow rate of ground water in the High Plains aquifer is expected to be small enough that the pumping test was able to capture most of the plume of the gravel-pack flow since the last period of pumping. For example, if the flow rate were as high as a foot per day, the plume from the new gravel-pack flow would have traveled 12 feet since the last pumping. The volume of water pumped during the pumping test would be equivalent to capturing ground water within a cylinder of radius 137 ft in the High Plains aquifer, assuming an average pumping rate of 358 gpm, homogenous flow, an average aquifer thickness of 18.4 ft, and an effective porosity of 25% from which water was withdrawn.

The first step in the estimation of gravel-pack flow from October 8 to 20 is computation of the percentage of water pumped with an alluvial aquifer composition at each sampling time in Table 8 during the concentration spike shown in Figures 37 and 38. The mixing equation

$$C_{mix} = vC_1 + (1-v)C_2$$

can be used to calculate the concentration of a dissolved constituent C in a mixture of two end-member waters, where v is the volume fraction of the first end member water. For this calculation, the chemistry of the pre-test sample is used for C_1 and is assumed to represent ground-water in the High Plains aquifer pumped at the end of the last irrigation withdrawal. Its composition would include long-term, past gravel-pack flow and leakage through the low-permeability layer at the end of that pumping. The composition of C_2 could be represented as an average of the alluvial aquifer water at sites PT1 and PT5. These wells were screened in the lower part of the alluvial aquifer (Table 10) above the low-permeability layer that separates it from the underlying High Plains aquifer. The variable C_{mix} is the concentration measured in the water for each sampling time.

The best constituents to use for the calculation are those that do not differ substantially between wells PT1a and PT5a in the High Plains aquifer, but differ substantially between the High Plains aquifer and the alluvial aquifer (wells PT1b and PT5b). Constituents such as calcium, magnesium, and sulfate differ enough between wells PT1a and PT5a that changes during the pumping test could be partly controlled by chemical heterogeneity in the High Plains aquifer. For example, there is a gradient of increasing specific conductance (and thus dissolved constituent concentrations) from well PT5a toward the Arkansas River channel as indicated by the values for wells PT1a, PT3, and PT4a (Table 10). Constituents such as sodium and chloride have relatively similar concentrations in samples from the High Plains aquifer (PT1a and PT5a), which differ substantially from concentrations in the alluvial aquifer (PT1b and PT5b). The chloride concentration in the samples collected from PT1a and PT5a differed by only 3.1 mg/L and averaged 57.6 mg/L (Table 9), a value essentially the same as the 57.4 mg/L in the pre-test sample (Table 8). The sodium content of the PT1a and PT5a samples differed by 5.9 mg/L and averaged 91.0 mg/L, which was only 9 mg/L lower than the pre-test concentration of 100 mg/L.

The values used for C_1 for chloride and sodium were the pre-test concentrations of 57.4 mg/L and 100 mg/L, respectively. The values used for C_2 for chloride and sodium in the alluvial aquifer were 97.6 mg/L and 186 mg/L, respectively, the averages for samples from wells PT1b and PT5b. The volume percentages of alluvial aquifer water in C_{mix} obtained from the computation for the samples collected up to 288 minutes after the start of the main pumping period using chloride and sodium concentrations were multiplied by the pumping rate at each sampling time to obtain a flow rate for alluvial aquifer water. The flow rate for alluvial aquifer water calculated from the mixing-curve equation for the 288 min sample was assumed to represent the combined leakage through the low-permeability layer and the gravel-pack flow occurring during the pumping test, and was subtracted from all the calculated flow rates for the previous sampling times. The area was calculated under the curves for plots of the flow rate contribution derived from the alluvial aquifer due to prior gravel-pack flow versus pumping time (Figure 41). This area (in gal) was divided by the time (17,165 min) between the end of the last period of irrigation pumping and the start of the O2003 pumping test to obtain the gravel-pack flow rate. The plot based on chloride concentrations is generally better than that based on sodium because it includes more sample points. The results, 1.4 gpm and 1.7 gpm based on the chloride and sodium data, respectively, suggest that the gravel-pack flow during period of no

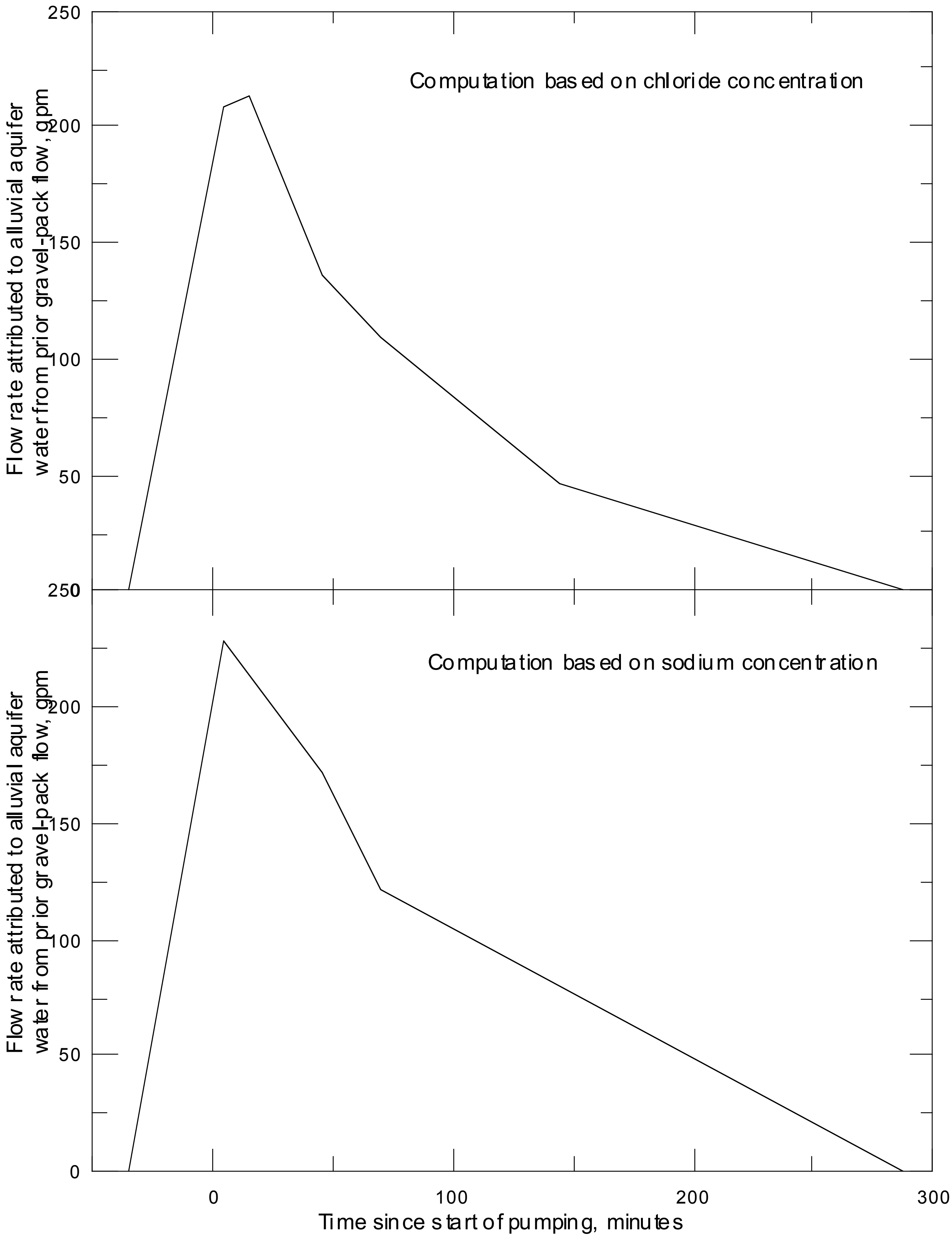


Figure 41. Change in flow rate attributed to alluvial aquifer water mixed with High Plains aquifer water during the initial concentration spike of the O2003 pumping test.

pumping is about 1.5 gpm at well IW. Uncertainties in the calculation include analytical error and how representative the pre-test sample was of the High Plains aquifer water at the end of the last pumping period. In addition, the fact that the samples from the alluvial aquifer (at PT1b and PT5b) were collected 3 months after the test and the specific conductance changed somewhat with time at one of the wells adds some uncertainty to the alluvial aquifer composition.

The flow through the gravel pack of well IW during pumping would be greater because the hydraulic head gradient between the alluvial and High Plains aquifers would be substantially larger than during static conditions. Based on the increase in hydraulic head between the two aquifers from approximately 1.8 ft before the pumping test to about 13.9 ft during the latter part of the test, the gravel-pack flow could have been around 12 gpm during the latter part of pumping.

The combined amount of gravel-pack flow and increase in leakage through the low-permeability layer separating the alluvial and High Plains aquifers during the latter part of the pumping test can be roughly estimated based on the small increase in the chloride and sodium concentrations from the pre-test sample to the end of the test. The increased leakage from the alluvial aquifer would be caused by the increased hydraulic head difference between the two aquifers resulting from the drawdown induced by pumping. The same mixing equation used above for determining the gravel-pack flow can be used for estimating the combined increase in gravel-pack flow and leakage at the end of the pumping test. Concentration C_1 and C_2 are the same, i.e., the composition of the pre-test sample and of the alluvial aquifer water. The composition of the water at the end of the pumping test is used for C_{mix}. The chloride concentration in the latter part of the pumping test ranged from 58.5 to 59.5 mg/L and fluctuated slightly by a few tenths of a mg/L from one sample to the next; part of the fluctuations could have been due to analytical error. A chloride value of 59.4 mg/L was used for C_{mix} based on a linear regression of the measurements for the samples collected from 1,229 min to the test end. The changes in the sodium concentration were smooth, from 101 to 105 mg/L after the concentration spike; the ending value of 105 mg/L was used for C_{mix} for the sodium-based computation.

If the pre-test chloride concentration of 57.4 mg/L is used for C_1 and the average for the alluvial aquifer of 97.6 mg/L is C_2, then the additional gravel-pack flow and low-permeability layer leakage from the alluvial aquifer causing the increase from 57.4 mg/L to the average of 59.4 mg/L would be equivalent to 5.0% of the total flow at the test end. Similarly, for sodium concentrations, if C_1 equals 100 mg/L (the pre-test value) and C_2 is 186 mg/L, then the additional gravel-pack flow and low-permeability layer leakage causing the increase from 100 mg/L to 105 mg/L would be equivalent to 5.8% of the total flow at the test end. An alternative approach is to use the chloride and sodium increase from the minimum after the end of the concentration spike to the end of the pumping test. In this case C_1 for chloride and sodium concentrations would be 58.6 mg/L (from the regression line for 1,229 min to the test end) and 101 mg/L, respectively. These values result in a combined increase in gravel-pack flow and leakage of 2.1% and 4.7%, respectively. The range of 2.1-5.8% represents a flow rate of about 8-21 gpm out of a total pumping rate of 358 gpm. As indicated above, this is a rough estimate because some of the increase could possibly be due to withdrawal of somewhat higher TDS water from different parts of the High Plains aquifer, such as indicated by the increase in specific conductance from the vicinity of well IW to the river. In addition to the uncertainties described for the gravel-pack flow estimate above, there is a significant lag time for the alluvial aquifer water to move through the low-permeability layer, so the leakage entering the top of the High Plains aquifer during the pumping test represents older ground water from the alluvial aquifer.

Summary

The water-quality data indicate that water pumped during the S2002 pumping test in the Arkansas River alluvial aquifer included some ground water from under the main river channel. Thus, if the river were flowing, river water would also have been expected to be drawn into the alluvial aquifer.

The effect of subregional pumping on the High Plains aquifer produces a lower hydraulic head in the High Plains aquifer than in the overlying alluvial aquifer. This results in downward flow of alluvial aquifer water through the low-permeability layer separating the aquifers. Depending on the age of the irrigation well, it can also result in downward flow through the gravel pack of the irrigation well. The water-quality effect of this flow was observed during the O2003 pumping test in the High Plains aquifer. When the river is flowing, the downward flow of water from the alluvium into the High Plains aquifer either decreases the discharge of alluvial ground water into the river or, if the river stage is greater than the water level in the aquifer, increases the discharge of river water into the alluvial aquifer. When the river is not flowing, this downward flow of water causes a water-level decline under the river channel. The induced flow of water from the alluvial aquifer to the High Plains aquifer also results in the downward migration of shallow water with more salinity and containing other constituents such as nitrate from surface sources. Chemical data collected as part of other projects in the area of the O'Rourke Bridge site supports this conceptual model. As indicated in the sections on the pumping test analysis, the lag time required for pumping in the alluvial aquifer to significantly affect river flow is expected to be substantially less than that required for pumping in the High Plains aquifer in the river valley, given equal distances of the pumping wells from the river.

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