KANSAS GEOLOGICAL SURVEY
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STREAM-AQUIFER INTERACTION ALONG THE ARKANSAS RIVER IN CENTRAL KANSAS: FIELD TESTING AND ANALYSIS

by

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Stream-aquifer interaction along the Arkansas River in Central Kansas:

Field Testing and Analysis

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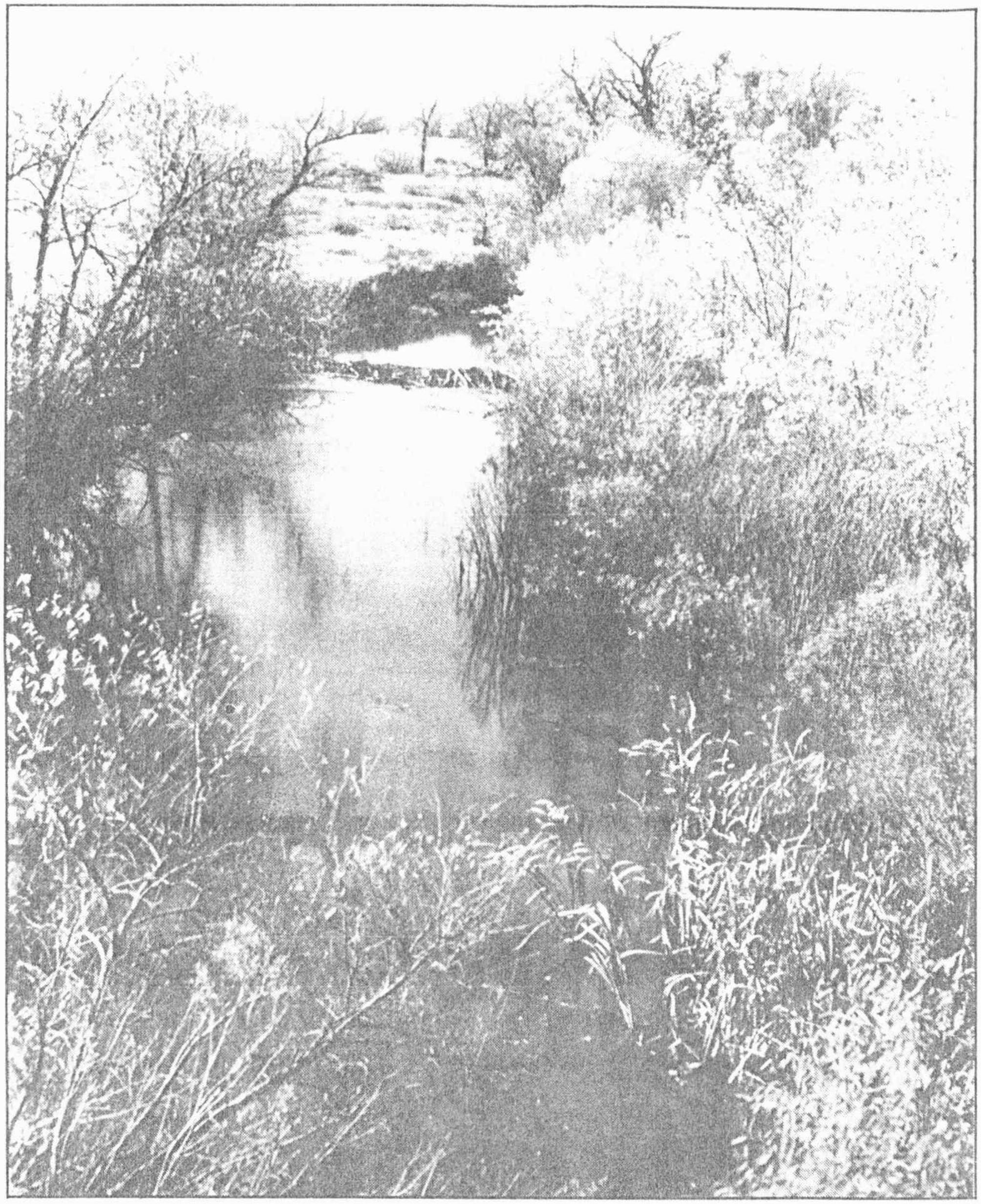
Project Completion Report to the Kansas Water Office



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ABSTRACT

During the last several years streamflows of a number of Kansas streams have been reduced as a result of ground-water declines. In order to better understand and quantify stream-aquifer interrelationships, an 8-day comprehensive stream-aquifer pumping test, followed by recovery monitoring was conducted along the Arkansas River near Great Bend, Kansas. In addition to water level monitoring in numerous observation wells, streamflow data, streambed hydraulic gradients, neutron probe-based moisture content of dewatered sediments, water chemistry and other data were collected. The alluvial aquifer is shown to be a highly transmissive one (T = 145,150 gal/day/ft) with the pumping stress (1,750 gal/min) having a radius of influence larger than 1.1 miles, impacting both the aquifer levels and the streamflow in the nearby Arkansas River. Drawdown and recharge-boundary effects were observed in all observation wells, including those on the opposite side of the river. The alluvial aquifer did not exhibit a water-table behavior and responded as a leaky confined aquifer. A less than 10-ft-thick semiconfining clay layer and an additional recharge source from a nearby stream-alluvial system were the probable causes of the observed phenomena. Actual streamflow depletion is shown to be appreciably less than the computed depletion based on analytical solutions.

ACKNOWLEDGMENTS

Several agencies offered personnel and other support which made this project phase possible. We would like to thank the Division of Water Resources, Kansas State Board of Agriculture, and especially the Stafford Field Office under Mr. Bruce Frisbie for making his personnel available for the field-testing program described in this report. Roger Clough and Jan Stryker provided streamgaging assistance, while Bruce Falk and Pat Dick provided water-level monitoring assistance during the pump test. We would also like to express our deep appreciation to Ralph Davis, manager of the Big Bend Ground Water Management District No. 5, who contributed his personnel and other logistical assistance to the field-testing program. In addition to Mr. Davis, Sharon Falk and especially Ned Marks provided substantial assistance to this project. We also express our appreciation to the Kansas Fish and Game Commission under Bill Hanzlick who also contributed personnel for this project. Ken Brunson provided water-level monitoring assistance during the pumping test. In addition, all three above-mentioned agencies through their named representatives volunteered to streamgage numerous sections along the Arkansas River from Kinsley to Great Bend on a twice-a-month basis during most of the 1986 calendar year.

Numerous KGS staff and students offered assistance during the testing period. Nadeem Shaukat, Pamela Chaffee, Howard O'Connor, Allen Macfarlane, Jamshid Sadeghipour, James

McAllister, Mike Kukuk, and Gary Costanzo provided needed assistance for this test. In addition, Nadeem Shaukat offered his surveying expertise for this project. Geoff Coble and Mike Kukuk provided data processing and display assistance.

We would also like to express our appreciation to the Kansas Water Office for partially funding this project and especially to Dr. Darrel Eklund for his interest and managing assistance for this project. Also, Dr. Manoutch Heidari of the KGS provided managing assistance during the proposal formulation stages of this project.

Finally, we would like to sincerely thank Mr. Dale Weller for letting us use his land as the test site and for accommodating all of our requests.

INTRODUCTION

During the last several years, streamflows of several western and central Kansas streams have been reduced as a result of ground-water declines along those streams. According to the Kansas Fish and Game Commission (KF&GC), fish and wildlife resources in and along the Arkansas River, Smoky Hill River, Pawnee River, Rattlesnake Creek, and other streams in western and south-central Kansas have been significantly impacted due to losses in baseflow (KF&GC, 1984)*. The implementation by the Kansas Legislature of the minimum desirable streamflow standards for some streams (and consideration of proposed minimum desirable stream-flow standards for others) have resulted in the need to examine the interrelationship of streamflow and ground water in the river alluvium and associated aquifers, which may contribute to the water available for base flows in these streams. According to the Division of Water Resources (DWR, 1984)*, a more thorough understanding of the stream-aquifer relationship in order to determine the effect of ground-water withdrawals on streamflows, both in terms of magnitude and duration, would be valuable during the administration of the minimum desirable streamflow program. Also, according to the KWO (1984)* specific information relating to lag times in stream depletion or recovery, well effects, effects of overall regional

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* Water Research Needs Conference, Wichita, Kansas, November 14, 1984.

appropriations, and effects of various pumping patterns is lacking. Such information is needed to justify administration of the program (KWO, 1984)*. "Stream Aquifer Interaction in General" was also identified in the highest priority category of research needs in the "Kansas Water Authority Annual Research Report (1986)."

The KGS, in response to this recognized problem, presented a 3-year multiphased research proposal to the KWO in 1985 in an open state competition for grants to address this problem. The awarded state funding for this project was on a year-at-a-time basis. The first phase of this project, which lasted for approximately one year, involved a comprehensive stream-aquifer pumping test in order to demonstrate and quantify the extent and nature of the interrelation of ground water and surface water and the fundamental hydrologic principles governing water movement. Due to the state financial crisis in 1986, funds were not available to carry out the remaining phases of the project involving stream-aquifer numerical simulation and management alternatives for the Kinsley to Great Bend reach of the Arkansas River. Therefore, this report will detail the results of the first phase of this project and outline some additional work also conducted during this phase.

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* Water Research Needs Conference, Wichita, Kansas, November 14, 1984.

PUMP-TEST SITE LOCATION

Originally, the test-site location was planned for the area around Kinsley in Edwards County. A detailed study of the geology of the area and several visits to the area showed that the saturated thickness there was of the order of a few tens of feet because bedrock (Dakota Fm.) subcropped very close to the surface, especially near the Arkansas River. In addition, the Arkansas River in that region was practically dry or nonflowing during the fall and winter of 1985 when attempts to locate suitable pump-test sites were made. In fact, at those times, the Arkansas River was not flowing throughout its reach from Kinsley to Great Bend. Only at Great Bend and further east was the river flowing. Therefore, a site near Great Bend (Barton County) in T. 19S, R. 13W., sec. 36, on property belonging to Mr. Dale Weller of Great Bend, was selected for the stream-aquifer pumping test (Fig. 1).

STREAM-AQUIFER PUMP-TEST DESIGN

A 20-inch-diameter pumping well, approximately 210 feet from the south bank of the Arkansas River, was constructed in April 1986, specifically for this test. The Clark Well and Equipment Company of Great Bend was contracted to do the drilling and well installation after a statewide bidding was conducted. The contracted drilling company also constructed a nest of two 5-inch-diameter observation wells approximately 50 feet southwest from the pumping well, one screened in the river alluvium and the

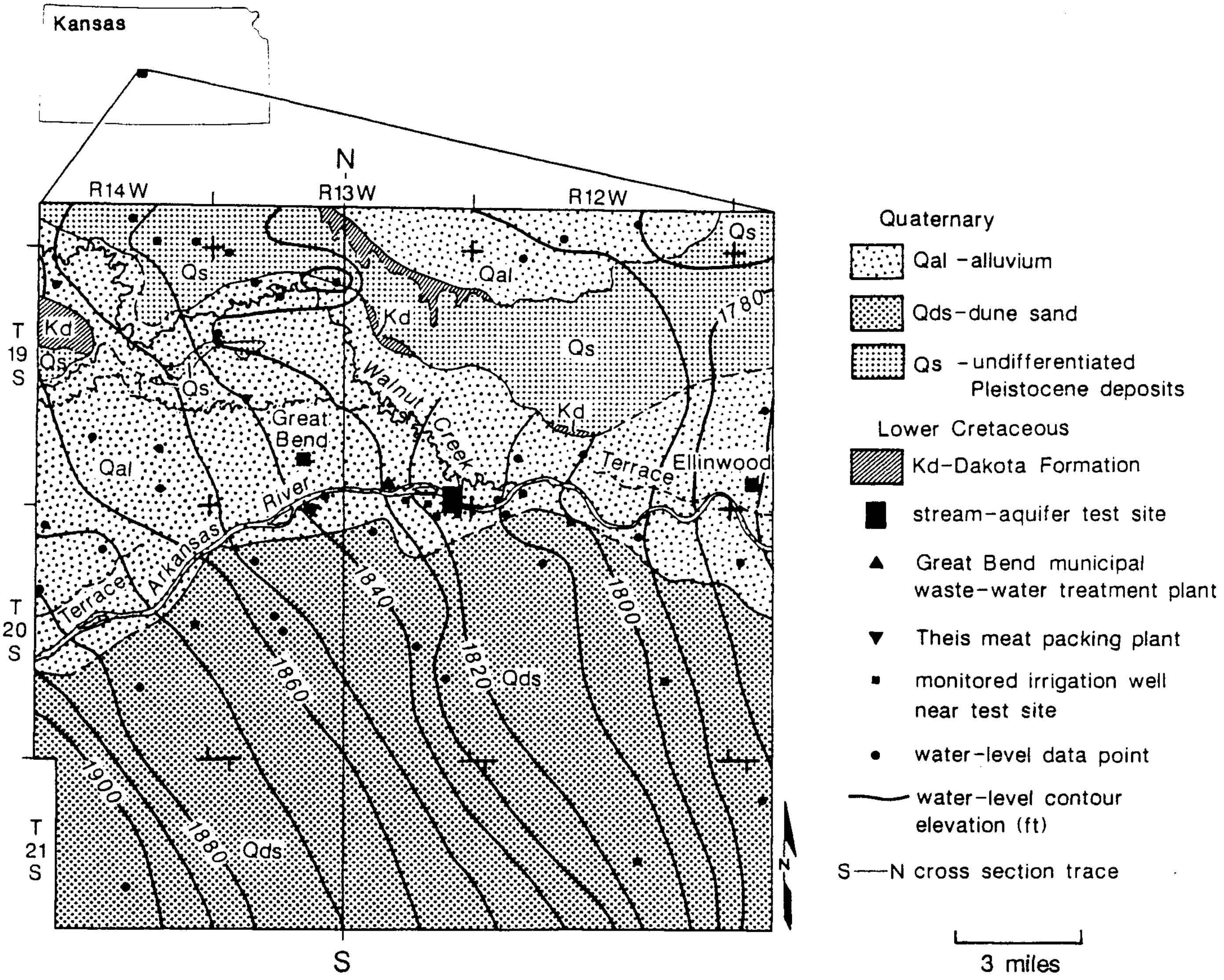

Figure 1. Location, general geology (adapted from Latta, 1950) and December 1986 water-level contours of the stream aquifer test site and vicinity

other in the bedrock aquifer immediately underlying the alluvium. KGS also drilled three 5-inch and 12 2-inch observation wells and installed eight 1.5-inch well points during the months of March and April 1986. The observation wells were located along lines approximately parallel and perpendicular to the Arkansas River as well as in other positions. Table 1 presents a summary of records for the wells in the stream-aquifer test area, and Fig. 2 depicts to scale the well layout at the site.

The numbering system for the test wells was one of approximate feet distance and direction from the pumping well. For example, the designation 100S means an observation well approximately 100 feet southwards from the pumping well. A flood-protection earth dike existed between the pumping well and the Arkansas River. All wells on the distant side of the dike are called north wells, while all wells on the pump-well side of the dike are called south wells.

A 44-foot-deep neutron probe-access tube made from galvanized steel pipe, with a watertight seal at the bottom, was installed approximately 25 feet from the pumping well. Five 0.75-inch-diameter minipiezometers with a 5-inch-long screen were inserted in the stream bottom at depths ranging from 2 to 6 feet. Seven seepage meters, constructed similar to those of Lee (1977) including a novel KGS-designed recording seepage meter, were installed in the streambed. A weather station consisting of a meteorograph for recording air temperature, relative humidity, and barometric pressure, and a mechanical weather-station unit

TABLE 1. SUMMARY OF RECORDS FOR THE WELLS IN THE STREAM-AQUIFER TEST AREA

Well I.D.	Radial Distance From PW (ft)	Depth (ft)	Well Diameter (in) & Mat'l	Screen Length[1] (ft)	Slot (in)	Land Surface Elevation[2] (ft)	Depth to Bedrock (ft)	Static Water Level Below Land Surface (ft)
PW	0	95.5	20S[3]	50	.100	1823.47	95.5	8.98
50S	57.5	94	5P[4]	43	.035	1824.05		9.91
50SBR	52.5	115	5P	15	.035	1823.89	97	9.68
100S	102.5	72	2P	15	.020	1823.87		9.85
400S	405	60	2P	15	.020	1821.24		8.52
600S	546.5	58	5P	20	.035	1820.78		8.29
300SW	462.5	70	2P	20	.020	1823.14		9.80
100W	102.5	75	2P	20	.020	1823.87		10.04
400W	386	60	2P	15	.020	1822.29		9.99
800W	769	55*(36)	5P	20	.035	1822.19		10.56
50E	45	80	2P	20	.020	1822.79		8.76
100E	102.5	70	2P	20	.020	1823.96		10.28
400E	405	60	2P	15	.020	1822.38		9.38
700E	687.5	55	5P	20	.035	1822.77		8.50
300SE	297.5	70	2P	20	.020	1821.96		8.44
100N	112.5	24	1.5WP[5]	4		1818.24		4.12
100NW	205	20	1.5WP	5		1819.89		5.64
100NE	257.5	19	1.5WP	4		1816.75		3.33
200N	215	15*(10)	1.5WP	5		1814.61		0.74
300N	315	22.5	1.5WP	5		1817.65		3.63
400N	436	21.5	1.5WP	5		1818.51		3.99
400NW	380	18.5	1.5WP	5		1818.16		3.65
400NE	516.5	19	1.5WP	5		1818.33		4.48
600NC	532.5	60	2P	15	.020	1826.47		9.96
600NW	564.	60	2P	15	.020	1826.63		8.93
600NE	652	65	2P	20	.020	1826.07		10.41
SW-IRR	2404	80	16S	40	.125	1817.71		7.43
W-IRR	2817	103	16S	48	.125			11.06
FW-IRR	5359	100	16S	40	.125		100	9.40
SE-IRR	2226	86	16S	40	.125			7.85

1. Wells screened from the bottom
2. Based on reference elevation of Corps of Engineers POT #27B, a Berntsen B-1 Monument, located in sec. 36, T.19S, R.13W, ~ 290 feet NW the 600 NW well
3. Steel
4. PVC
5. Well point (steel)

* Well cracked with sand & gravel caving into depth indicated in parentheses

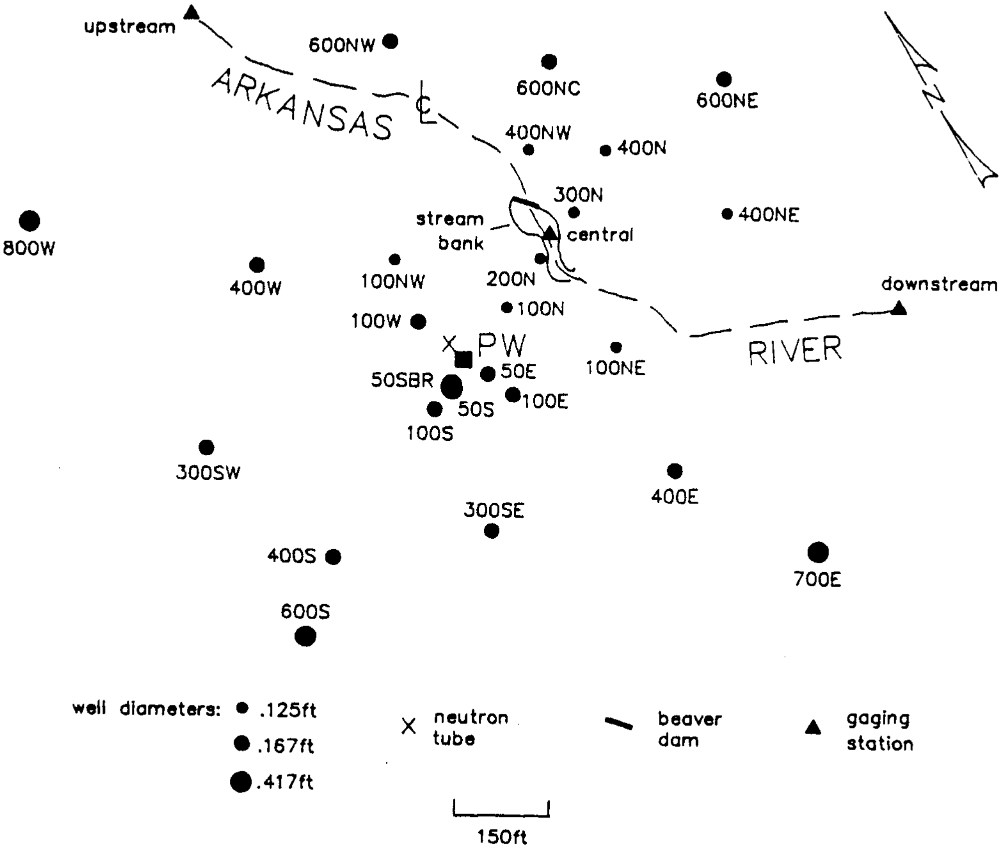

Figure 2. Observation-well layout at the stream aquifer test site

with a tipping bucket rain gage recording rainfall, air temperature, wind speed, and direction were also installed at the site.

Three stream-gaging stations designated as upstream, center, and downstream, separated by a distance of approximately 800 feet (Fig. 2), were selected for monitoring during the test. Each station was equipped with a staff gage. In addition, four nearby irrigation wells (Fig. 1) were selected for monitoring during the test.

The test was planned to be run for up to two weeks, to be followed by recovery monitoring. The pumped water was diverted back to the river, approximately 1,000 feet downstream from the pumping well, using standard irrigation pipe.

TEST LOGISTICS

Because of the distance of the test site from the KGS base station in Lawrence (approximately 230 miles away), a major logistics operation was undertaken. A trailer and portable bathroom facilities were rented and positioned at the pump-test site. Lighting arrangements through portable generators were installed at the site. The trailer was equipped with all necessary materials and supplies for conducting the test. A high-capacity pump was rented and installed on the constructed well and was fueled from a large-capacity fuel tank installed next to the pump. Because of unexpected delays in drilling and completing the pumping well, the planned step-drawdown test was not run. Prior to the pumping test, Stevens recorders (Type F) were placed on some wells to monitor any water-level trends prior to the test. Also, selected observation wells were sampled for water-quality analysis prior to the test.

Because of the large number of observation wells at the site, the manpower requirements were high. To economize on field personnel, three Stevens water-level recorders were installed at the most distant 5-inch-diameter wells from the pumping well (800W, 700E, 600S), expecting that the most distant wells would show smaller water-level declines. The recorded water levels at the site prior to pumping were stable. The water-level recorders were set to one complete revolution in 12 hours (the shortest time range on the recorder quartz clock) during the test. Three pressure transducers (two connected to a Hermit and one on an SE1000 data-logging unit, both from In-Situ, Inc.) were also installed: one in the pumping well, one in the 50S well screened in the consolidated aquifer underlying the alluvial aquifer, and one in the 50E well, which failed to function during the test. In order to further economize on personnel, the 2-inch 400S, 400E, and 400W wells were converted to recording wells during recovery by specifically constructing 1-inch PVC float tubes and specially adjusting the type-F Stevens recorders so that the recording drum was speeded up to a complete revolution in 6 hours instead of the shortest factory preset time of 12 hours. Several state and local agencies, in addition to KGS staff and students, offered to help in this test to ease the manpower requirements. To further reduce manpower requirements, the pump-test duration was reduced to eight continuous pumping days. The assignment of responsibilities was as follows: One person each manned the 50E, 50S, 100W, 100N, and 100S observation wells using electric water-level measuring tapes for faster water-level readings because these wells were expected to show the largest drawdown. One person was assigned to man the neutron probe and inspect the pump and flow meter, another one to measure the 400E and 300SE wells, and another one to man the 400W, 300SW, and 400S wells. One person was responsible for the 100NW, 100NE, and 200N observation wells, another for the 300N, 400NW, 400N, and 400NE, and another for the 600NE, 600NC, and 600NW wells. A person was assigned at the minipiezometer stream site and was also responsible for periodic seepage meter readings. Two persons were assigned for streamgaging the three preselected river sections, and one was assigned to measure the nearby irrigation wells and inspect the water-level recorders. The contracted driller was responsible for inspecting the pump assembly and fuel tank. A person was assigned to periodically sample both the pumped water, through a faucet in the discharge pipe, and the river water. This large amount of manpower was maintained for the first two days of drawdown and the first day of recovery monitoring, although with somewhat reduced manpower. A high frequency of water-level readings was maintained during the first two hours and especially during the first half hour after the pump was turned on.

The pumping started at 13:02 (CST) on April 21, 1986, and was maintained at approximately 1,750 gpm until 13:01 (DST) on April 29, 1986. A McCrometer flow meter was installed on the pumping-well discharge pipe. Frequent checks of the water meter were made and the pumping rate was adjusted accordingly if large deviations in the pumping rate were observed. The pumped water was diverted back to the river downstream from the pumping well through a 9-inch irrigation pipe approximately 1,000 feet long. After completion of the test, a land survey was done using a microptic theodolite.

GEOLOGY AND INITIAL CONDITIONS

The surficial geology of the area is that of a typical river-alluvium environment consisting of generally coarse granitic sands and gravels intermingled with relatively thin clays. The surface is partially covered by dune sand forming relatively low mounds. The generalized geology of the region around the pump-test site and a north-south cross section near the pump-test site both adopted from Latta (1950) are shown in Figs. 1 and 3, respectively. Fig. 1 also depicts the water-level pattern in the area for a water-level survey of the Arkansas River valley from Kinsley to Great Bend conducted during December 1986. A general west-to-east flow direction along the river alluvium is present. Table 2 presents a generalized section of the geologic formations in the area.

Bedrock consisting of fine-to-medium yellowish sandstone with very thin yellowish clay streaks was encountered at approximately 96 feet below land surface. At the 115-foot

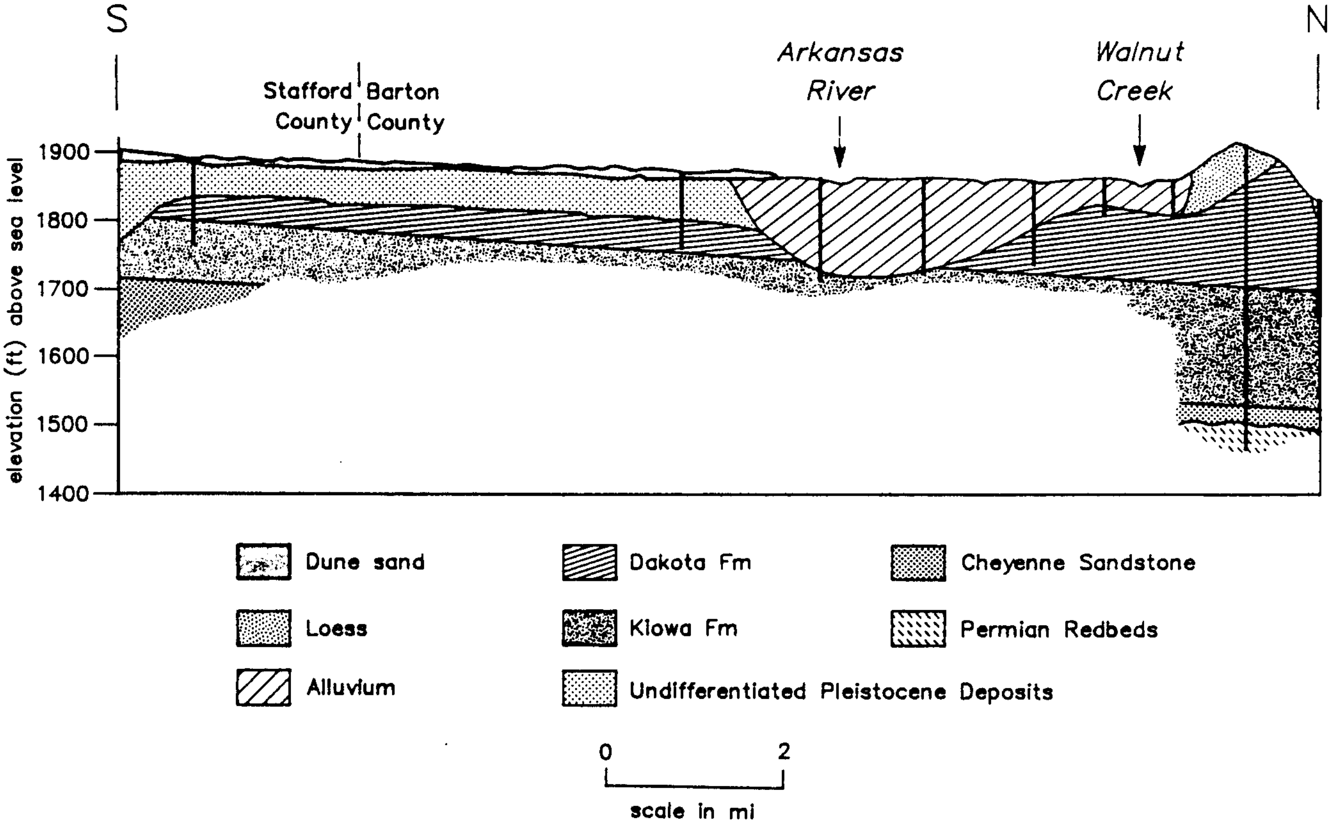

Figure 3. North-south geologic cross section near the stream aquifer test site indicated in Figure 1 (adapted from Latta, 1950)

Table 2. GENERALIZED SECTION OF THE GEOLOGIC FORMATIONS IN THE TEST AREA AND VICINITY (FROM LATTA, 1950).

System	Series	Subdivision	Thickness	Physical character	Water supply
Quaternary	Recent and Pleistocene	Alluvium Unconformable on older formations	0-125	Very coarse gravel, sand and silt comprising stream deposits in the larger valleys and Cheyenne Bottoms. Includes deposits underlying low terrace on the north side of Arkansas River and marsh deposits beneath Big and Little Marshes in northeastern Stafford County.	Yields large amounts of water to wells in Arkansas and Walnut Valleys and small to moderate amounts to wells in Cheyenne Bottoms and smaller stream valleys. Supplies water to many irrigation and a few industrial wells in Arkansas and Walnut Valleys. Waters in most places are hard, but otherwise are satisfactory for most purposes. Waters of poor quality found in Cheyenne Bottoms and Big and Little Marshes.
		Dune sand Unconformable on older formations	0-50+	Fine- to medium-grained wind-blown sand containing minor amounts of silt, clay, and coarse sand. Covers most of the area in Barton and Stafford Counties south of the Arkansas River and a small area on the east side of Cheyenne Bottoms.	Not known to yield water to wells. Areas underlain by dune sand are excellent areas for ground-water recharge from local precipitation.
	Pleistocene	Sanborn formation Unconformable on older formations	0-138	Silt, sandy silt, and fine sand that locally contains lenses of coarse sand and gravel. Occurs beneath Cow Creek drainage basin, Cheyenne Bottoms-Arkansas Valley divide area, and Dry Walnut Valley-Arkansas Valley divide area, and includes terrace deposits along north side of Walnut Valley and along Dry Walnut Valley.	Supplies water to domestic and stock wells in the Cow Creek drainage area and the Walnut Valley terrace area. Large supplies available from these deposits locally in Walnut Valley terrace area. Waters from the Sanborn formation are moderately hard to hard, samples ranging from 242 to 606 parts per million in hardness.
		Meade formation Unconformable on older formations	0-210+	Interbedded lenses of unconsolidated gravel, sand, and silt. Caliche is common throughout the formation. Meade formation occurs at the surface or at shallow depth beneath dune sand or alluvium over all Stafford County and the southern part of Barton County.	Sand and gravel beds of the Meade formation are the most important sources of water in Stafford County and southern Barton County, and yield large supplies. Most of the domestic and stock wells and all of the irrigation and public-supply wells south of Arkansas Valley derive water from these deposits, and many of the domestic, stock, irrigation, and industrial wells in Arkansas Valley and the city-supply wells at Great Bend derive all or a part of their water from this formation. In most areas the water is of good quality, but locally it is highly mineralized.
		Undifferentiated pleistocene deposits Unconformable on older formations	0-40	Unconsolidated silt, sandy silt, and clay that contains caliche, and, locally, thin lenses of sand and gravel. Restricted to relatively small area surrounding Galatia in northwestern Barton County.	Supplies water to a few domestic and stock wells in the vicinity of Galatia.
Tertiary	Pliocene	Ogallala formation Unconformable on older formations	1-3	In northern and western Barton County, "algal limestone" from less than 1 to 3 feet thick caps small hills at widely scattered localities.	Not known to yield water to wells in this area.
Cretaceous	Gulfian*	Carlile shale (Fairport chalky shale member)	85 (?)	Chalky shale and thin beds of chalky limestone, containing thin flat concretions in the lower part.	Furnishes small to meager supplies of hard to very hard water to a few dug domestic and stock wells in northern Barton County. Not an important water bearer.
		Greenhorn limestone	85-90	Chalky tan to blue-gray shale, alternating with beds of hard chalk; contains thin beds of hard crystalline limestone in lower part.	Furnishes small to meager supplies of water to a few domestic and stock wells in northern Barton County. Not an important water bearer.
		Graneros shale	30-40	Noncalcareous light-gray to blue-gray and brown shale; contains selenite, pyrite, and thin beds of fine-grained sandstone.	Relatively impermeable; not known to yield water to wells in this area.
		Dakota formation	200-300	Alternating beds or lenses of varicolored clay, shale, siltstone, and fine- to coarse-grained sandstone. Contains "ironstone" in thin beds, lignite, and a little pyrite.	About a third of the recorded wells in Barton County derive water from sandstones of the Dakota formation. Is the chief source of water in the upland areas of Barton County. Supplies water to city wells at Claflin and Ellinwood. Yields of wells range from a few gallons a minute to a few hundred gallons a minute. Some wells yield water of good quality, but others yield water too highly mineralized for ordinary uses.
	Comanchean*	Kiowa shale	90-168+	Light-gray to black shale and sandy shale, containing beds or lenses of fine- to medium-grained sandstone and thin beds of hard calcareous sandstone and sandy limestone. Pyrite, gypsum, shell fragments, and cone-in-cone calcite are common. Exposed in two small areas, in southeastern Barton County and northeastern Stafford County.	Unimportant in this area as a water bearer. One recorded well (20-11-12ad) in Barton County taps sandstone of the Kiowa shale. In most of this area water in the Kiowa is probably highly mineralized.
		Cheyenne sandstone	0-134+	Sandstone, very fine- to medium-grained, siltstone, and some clay and shale. Not exposed in Barton and Stafford Counties.	No wells in Barton and Stafford Counties obtain water from the Cheyenne sandstone. Scanty data indicate that the water in this formation is highly mineralized and unfit for ordinary uses.
Permian	Guadalupian and Leonardian*	Undifferentiated red beds		Red siltstone, shale, and sandstone containing lesser amounts of salt, gypsum, anhydrite, limestone, and dolomite. Not exposed in Barton and Stafford Counties	No wells in Barton and Stafford Counties obtain water from Permian rocks. Water is probably too highly mineralized for most ordinary uses.

* Classification of the State Geological Survey of Kansas.

interval of the bedrock observation well (50SBR), a very hard white quartzose sandstone was encountered which the rotary drill was unable to penetrate. It is inferred that the formation below the alluvium is a sandstone bed in the Kiowa Formation, although a Dakota Sandstone interpretation is not excluded because an iron-stained sandstone cobble typical of the Dakota Formation was removed from the bottom of the pumping-well borehcle.

The pump-test geology, based on drillers' logs and gamma-ray logs from a geophysical logging survey conducted by KGS for this study, is shown by the fence diagram of Fig. 4. A clay layer of varying thickness and depth, but of approximately continuous extent, is evident around the 30-to-40-foot depth interval. This clay layer comes closer to the surface in the pumping-well vicinity. Another thinner and more discontinuous clay layer is evident above the main clay layer. These clay layers have significant implications for interpreting the results of the stream-aquifer pumping test as will be discussed later. Generally, a coarsening of the sand and gravel sediments is observed with depth, especially below the clay layer.

Because of difficulties with accurate sampling with the Survey's drilling equipment and also because the geophysical logging vehicle was not available at the time of drilling, the later-interpreted continuity of the above-mentioned clay layer was not recognized at the time. The prevailing wisdom at the time was that we had a typical alluvial system with discontinuous and intermingled clay lenses which could not be confidently

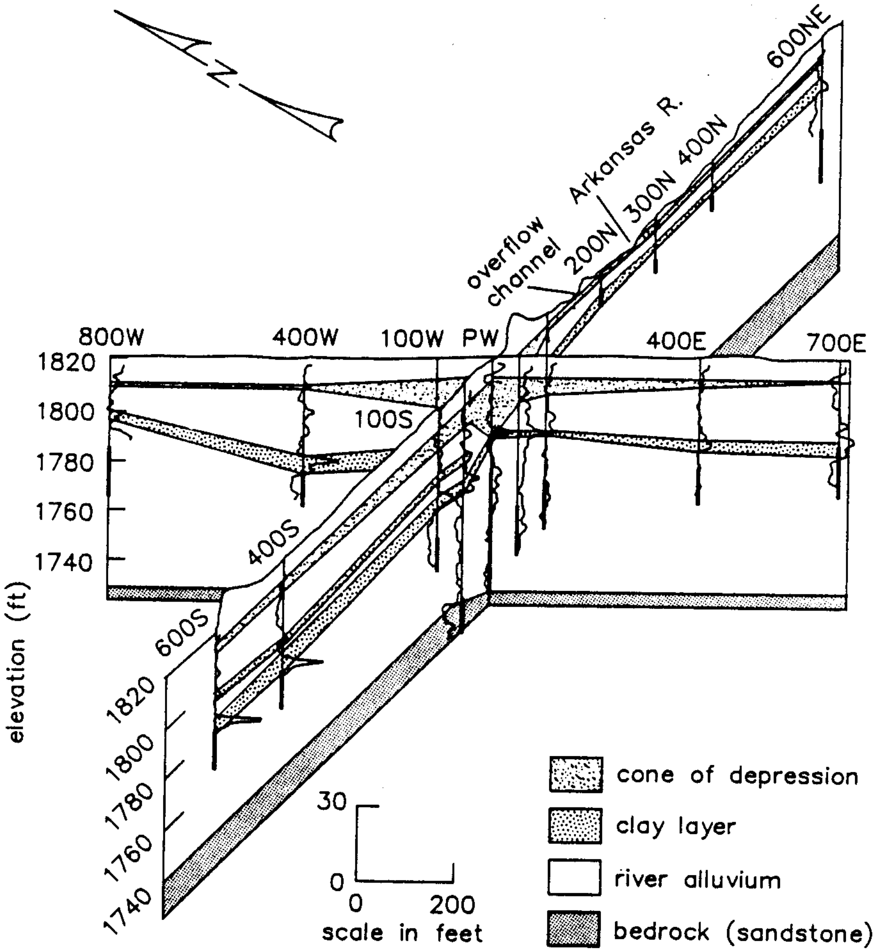

Figure 4. Fence diagram of the stream-aquifer test site showing major lithologic units based on gamma ray logs and drillers logs. Cone of depression just before pump shut down is also shown. Thickened portions of vertical lines (observation wells) indicate screen intervals

correlated over the pump-test site.

The static water-level configuration at the pump-test site (Fig. 5) showed an elongated "bulge" approximately parallel to the Arkansas River. This indicates a local ground-water divide with a flow component towards the river and another one southwestwards away from the river at the pump-test site. The regional ground-water gradient is generally from west to east and along the river course (Fig. 1). Water-level surveys conducted after the pumping- and recovery-test period (May 1, 1986, and December 1986), showed the same ground-water-level pattern, indicating that the earlier-mentioned clay layer most likely creates a "perched" water-level condition in that area.

COMPLICATING CONDITIONS DURING THE TEST

While the drawdown test was underway, the nearby irrigation wells (Fig. 1) (with the exception of the SE irrigation well) started pumping at different times, stopped for a short time interval, and resumed pumping again. All these irrigation wells stopped pumping when a rainstorm started. This 2-inch rainstorm created a high stream stage on April 27 and 28. Table 3 details the chronology of these complications. In addition to these complications, the pumping rate was difficult to maintain at a constant level during certain time intervals, especially during the first minute, during the 10 to 21 minute time interval and around the 2740-2750 minute period. During the 10 to 21 minute time interval, the pumping rate was manually adjusted because the pumping rate was rapidly decreasing down to 1,600 gpm by the 15th

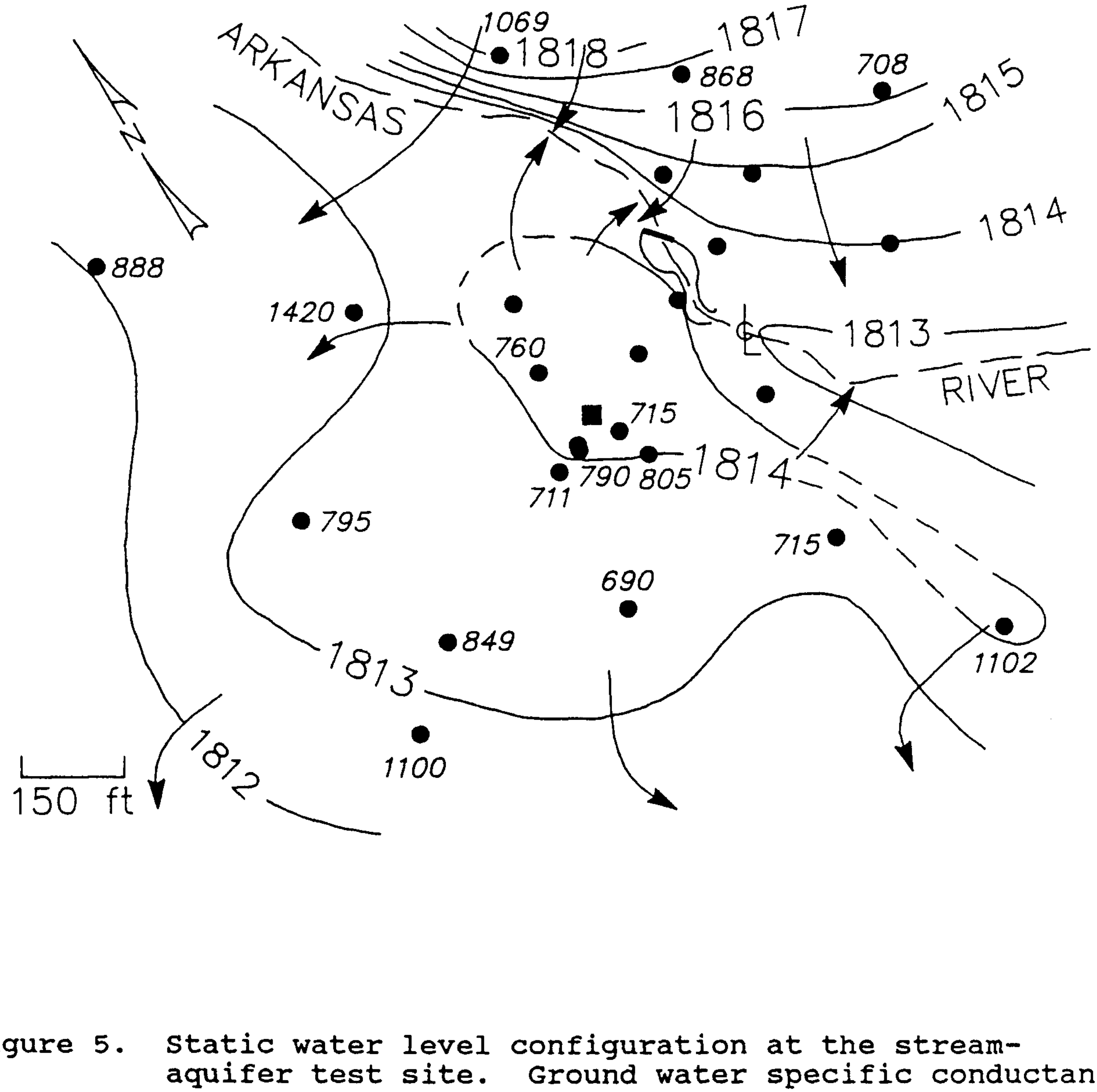

Figure 5. Static water level configuration at the stream-aquifer test site. Ground water specific conductance values (in italics) taken after the completion of test are also shown

elapsed minute instead of the scheduled 1,700 to 1,800 gpm range. Because of the lack of fine-tuning knobs, the throttle adjustment resulted in increasing the pumping rate to 1,900 gpm around the 20th minute, which was readjusted to the approximate 1,750 gpm range by the 22nd minute. The McCrometer needle was fluctuating almost constantly between the 1,700 and 1,800 gpm mark throughout the duration of the test.

TABLE 3. SCHEDULE OF NEARBY IRRIGATION-WELL OPERATIONS

Date	Time	Elapsed Time since PW Started Pumping (min)	SW-IRR	W-IRR	FW-IRR
4-24	8:10 AM	4028	ON	OFF	OFF
	~12:15 PM	4273	OFF	OFF	OFF
	1:30 PM	4348	OFF	ON	OFF
4-25	10:27 AM	5605	OFF	OFF	OFF
	2:05 PM	5823	OFF	ON	OFF
	4:48 PM	5986	OFF	OFF	OFF
	6:28 PM	6086	OFF	OFF	ON
4-26	9:21 AM	6979	ON	OFF	ON
	10:00 AM	7018	ON	OFF	OFF
4-27	~2:30 AM	8008	OFF	OFF	OFF

In addition to the above-mentioned problems, a 2-inch rainstorm occurred in the early morning hours of April 27, with subsequent light drizzle throughout that day. An air-temperature, relative-humidity, and barometric-pressure recording chart at the weather station installed at the site for this project is shown in Fig. 6 for the entire duration of the test. The rainstorm can be easily recognized by the lowering of

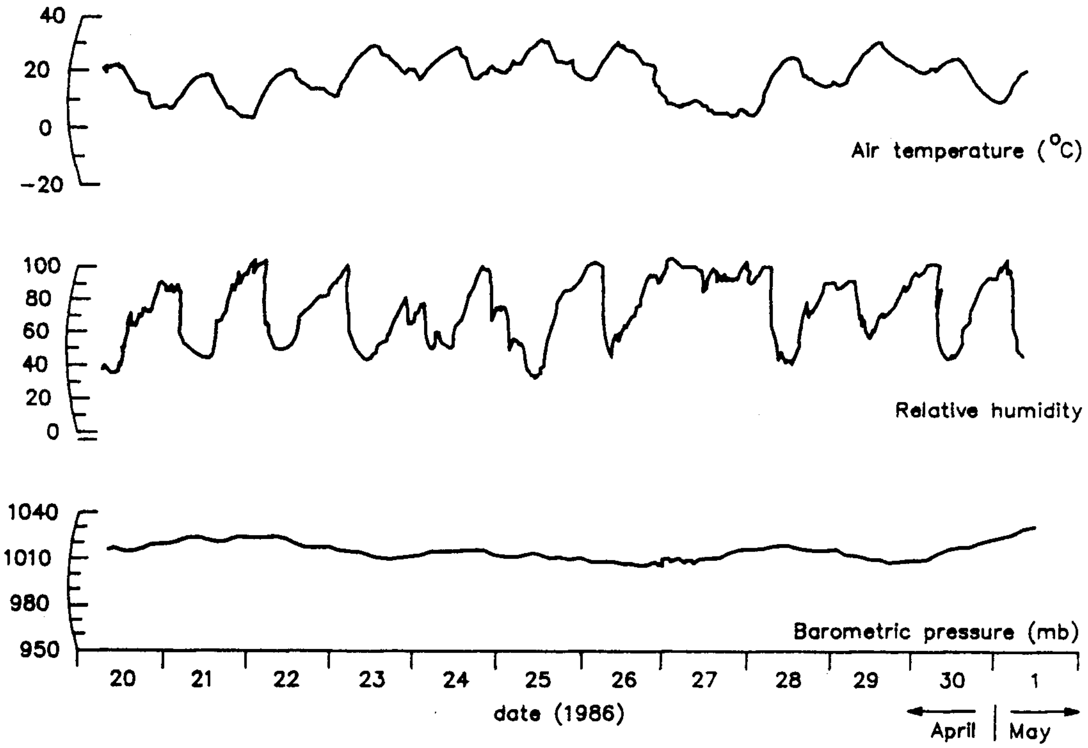

Figure 6. Meteorograph record of air temperature, relative humidity and barometric pressure at the test site for the test duration

temperatures, extended periods of high relative humidity, and the lowering of the barometric pressure immediately preceding the storm. However, no significant barometric-pressure changes were observed during the test period.

STREAM RESPONSE TO PUMPING

As shown in Figure 2, three river sections were being monitored during the pump-test period using pygmy water-current meters. One river section was straight across from the pumping well and two others 700 to 800 feet upstream and downstream from the central river section. It should be noted that a beaver dam was present immediately upstream of the central gaging station (Figure 2). Also, immediately above the upstream gaging station another beaver dam was present. These beaver dams are typical along the Arkansas River in that region. A stream-level recorder was used to record stream stage inside a perforated drum emplaced on the streambed near the central streamgaging section.

The municipal waste-water-treatment plant for the city of Great Bend is located approximately 1.5 miles west of the pump-test site (Figure 1). The treatment plant released a daily average effluent of 3.77 cfs to the Arkansas River during the pump-test period. Also, the Great Bend Theis Meat Packing Plant, located approximately 3 miles west of the pump-test site (Fig. 1), released a daily average of 1.3 cfs to the stream. The daily discharges from the two plants were fairly constant, as can be seen in Figure 7. However, the hourly discharges, especially from the municipal waste-water-treatment plant, fluctuated widely

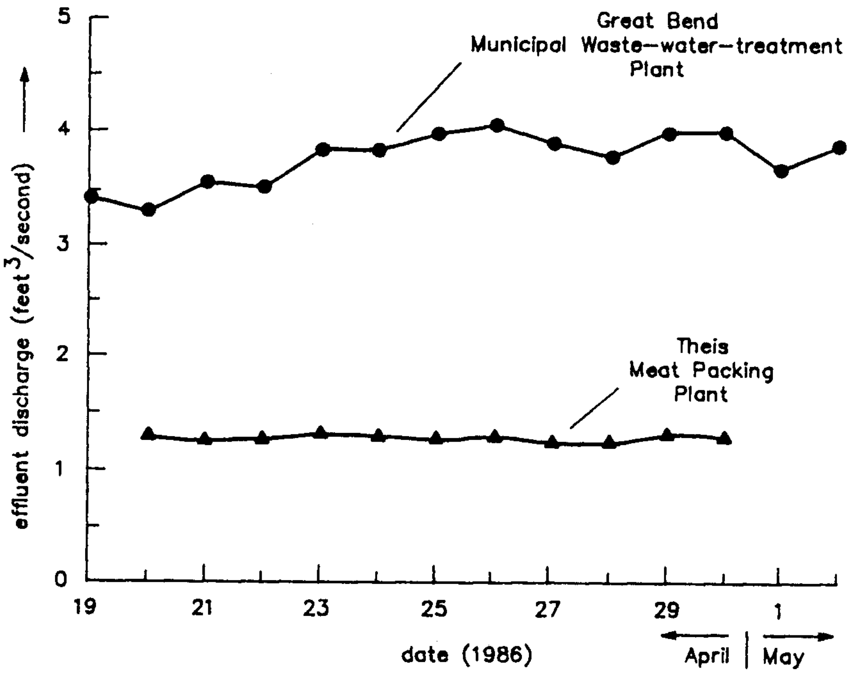

Figure 7. Daily effluent discharges to the Arkansas River from the two plants shown in Figure 1

although in a fairly constant manner as shown in Figure 8. This effluent variability is significant because it affected the hourly streamflow discharge and stage of the Arkansas River further downstream.

A record of stream stage during the pump-test period is shown in Figure 9. A stream-stage-decline pattern is evident once the pumping phase started (time 0). This decline was temporarily interrupted by the rainstorm around the 8100-minute mark. The decline of stream stage stopped only after the pumping stopped at approximately 11,500 minutes after the start of the test. Figure 9 also shows the effect of effluent releases to the stream on the pattern of stream hydrographs, indicating that these fluctuations are not the result of evapotranspiration processes. If that were the case, one would expect high stage (and flows) during the night and early morning hours which is contrary to what is observed. Figure 10 shows the same declining pattern with regard to streamflows. Streamflows declined from approximately 7 cubic feet per second (cfs) at the start of the test to approximately 1.8 cfs by the fifth day of pumping just before the rainstorm occurred. The decline stopped right after the pump was turned off at 11,459 minutes (Figure 10). Figure 11 shows streamflow differences between the downstream- and central-gaging stations. It is evident that throughout the duration of the pump test, the 700-foot stream reach was losing water (with the exception of the rainstorm period) and that only after the pump was shut off did the reach return to its natural

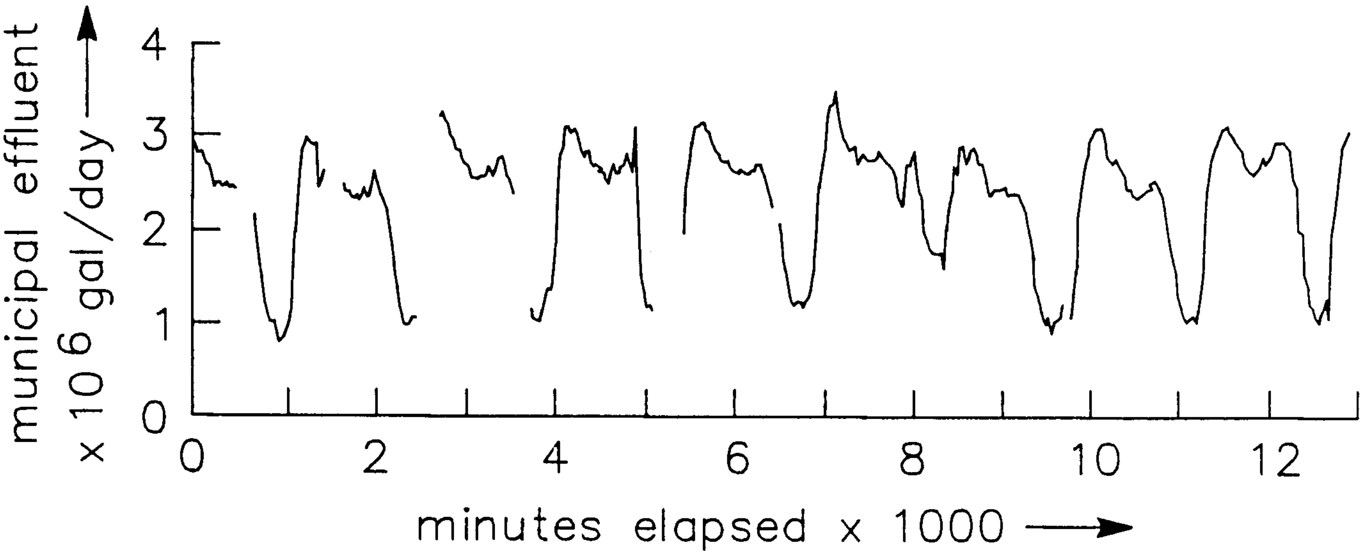

Figure 8. Continuous effluent release curve to the Arkansas River from Great Bend municipal waste-water-treatment plant during the test period

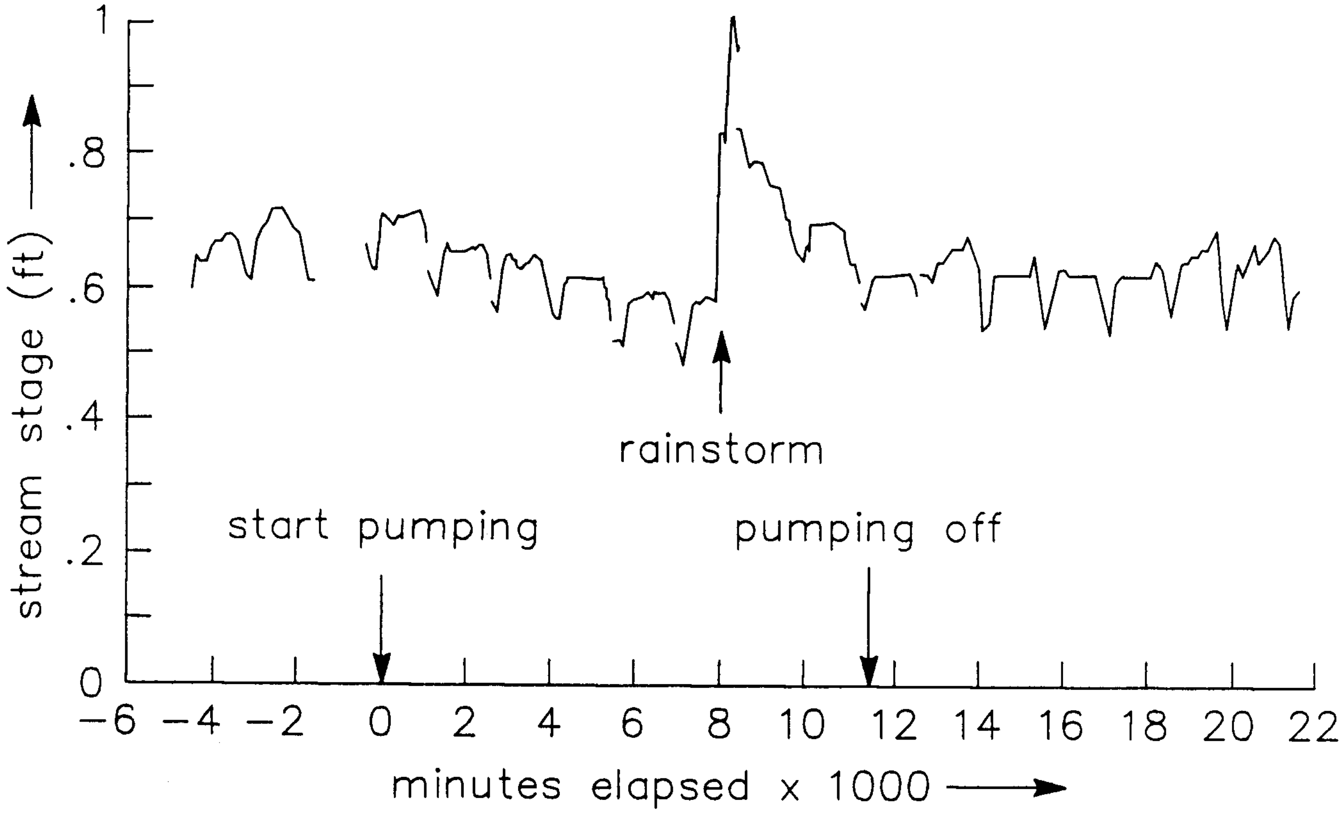

Figure 9. Arkansas River stage hydrograph during the test

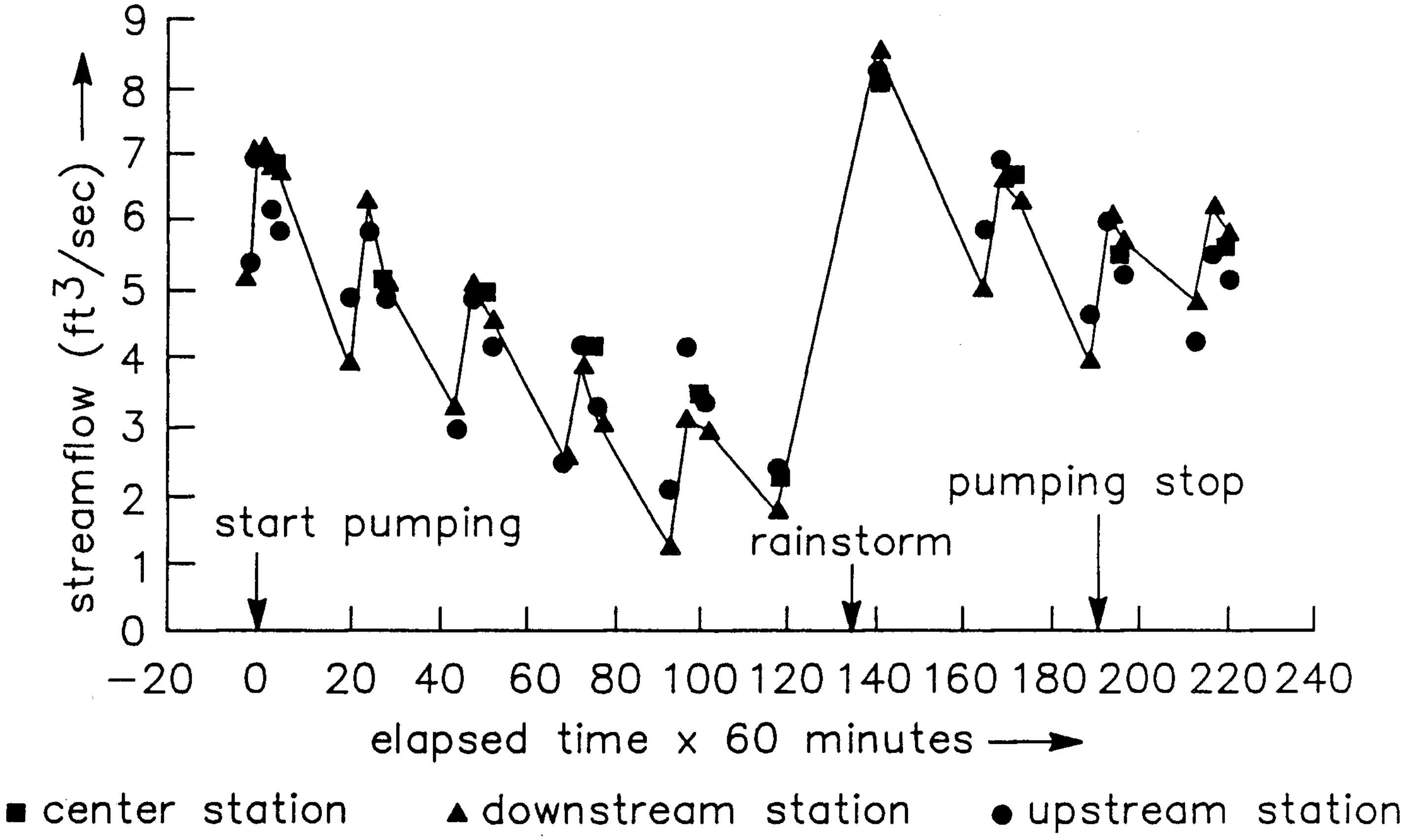

Figure 10. Arkansas River streamflow hydrograph during the test

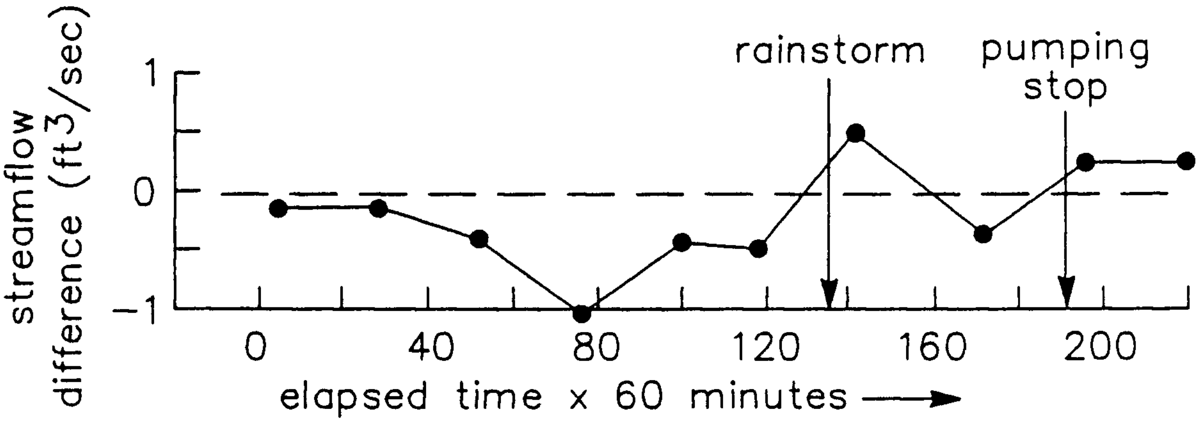

Figure 11. Streamflow-difference hydrograph between the downstream and central gaging stations on the Arkansas River during the test

"gaining" condition. Excluding the flooding event of April 27, 1986, the average streamflow (seepage) loss across this 700-foot streamreach during the pump-test period was 0.45 cfs (38,880 ft^3/day; 290,822 gpd) while the streamflow gain after the pumping was stopped was 0.22 cfs (19,008 ft^3/day; 142,180 gpd) across the same reach. This latter value most probably represents the natural streamflow gain over that reach.

Five minipiezometers, constructed by KGS, were installed in the streambed near the central gaging station at depths of 2, 3, 4, 5 and 6 feet. The stream was very shallow (approximately half a foot deep) with an average approximate width of 18 feet at the pump-test site. The streambed consisted of gravel and coarse sand, with no significant silt layer evident. A reference horizontal line was marked on the minipiezometer standpipes and all measured minipiezometer water levels were referenced to that datum for consistency because the sand and gravel streambed was constantly changing due to sediment transport and streambed scouring. A plot of water levels from the minipiezometer nest (Figure 12) indicates that prior to the pumping test, upwards gradients from the alluvial sediments to the streambed were in existence making the stream in that vicinity a gaining one. As soon as the pump was turned on (time = 0 min), these gradients were reversed and became downward gradients from the streambed to the underlying sediments, making the stream in the same vicinity a losing one, and induced infiltration was initiated. This situation continued until the pumping well was shut off,

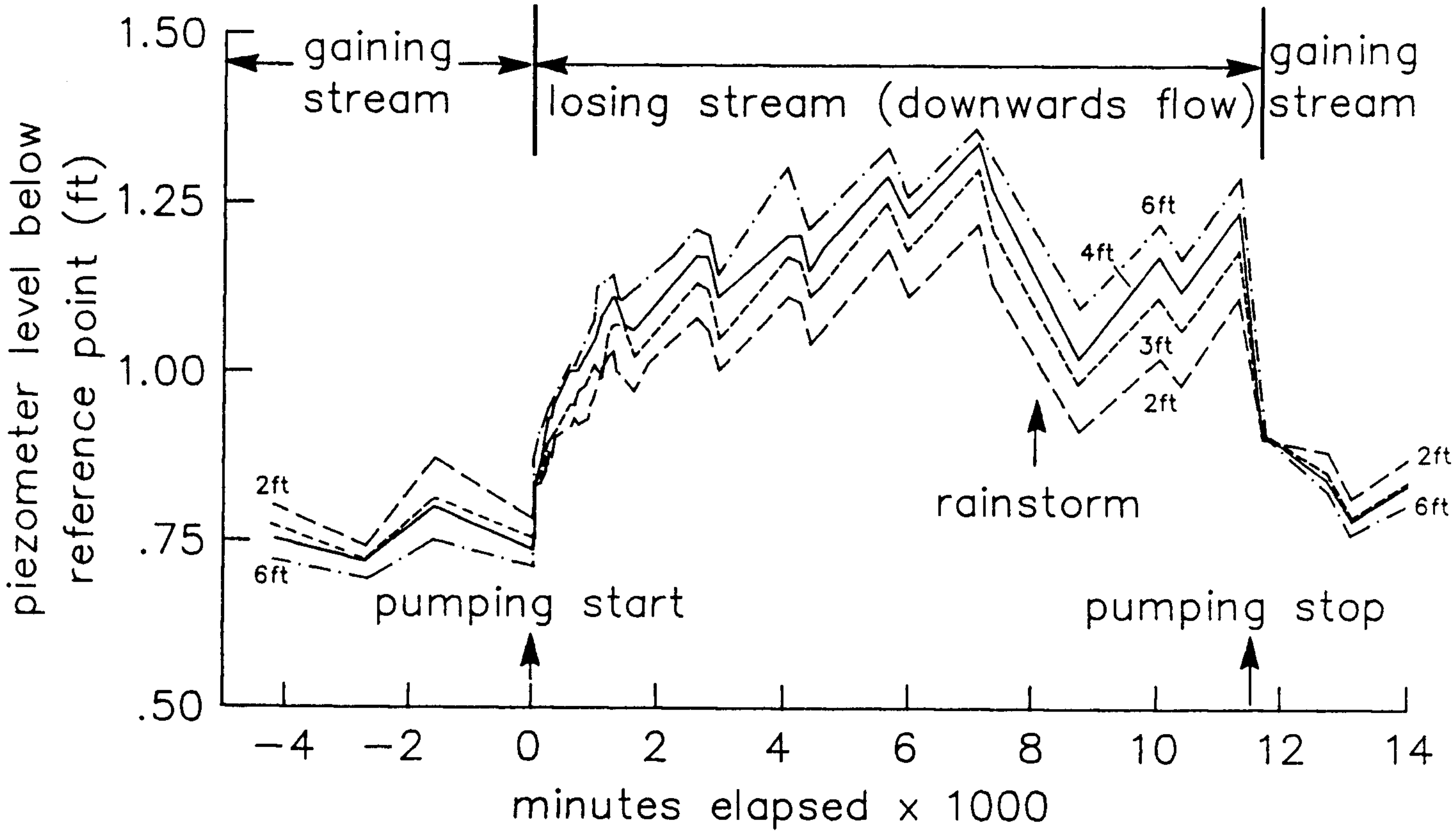

Figure 12. Water level hydrographs from minipiezometer nest in streambed sediments during the test

immediately after which the minipiezometer gradients were again reversed to their natural condition. Streamflow fluctuations and the high streamstage resulting from the rainstorm are reflected in the minipiezometer response as well (Figure 12). Analysis of water-chemistry data also supports the stream-aquifer interaction as will be further discussed in the chemistry section.

Analysis of the seepage-meter data indicated that due to the highly permeable nature of the streambed and the shallow depth of insertion (8 inches), the seepage meters were probably unable to hermetically isolate the streambed area covered by them, resulting in a high degree of correlation between stream stage and flow through the seepage meters.

AQUIFER AND OVERLYING SEDIMENT RESPONSE TO PUMPING: SOME FUNDAMENTAL QUESTIONS

A typical drawdown-recovery response from a well with a recorder on it is shown in Figure 13 for the 600S observation well. A sharp initial drawdown as well as a sharp initial recovery are evident from the hydrograph. Also, the effects of the on and off pumping of nearby irrigation wells are sharply evident in the hydrograph. The fact that the rate of drawdown was sharply reduced after the first few minutes of pumping are indicative of a recharge and/or leakage effect. Figure 14a depicts the drawdown versus time on a semilog graph for the 100S observation well which is representative of the alluvial wells. The drawdown versus time for all observation wells was first plotted on semilog graph paper because any deviations of the

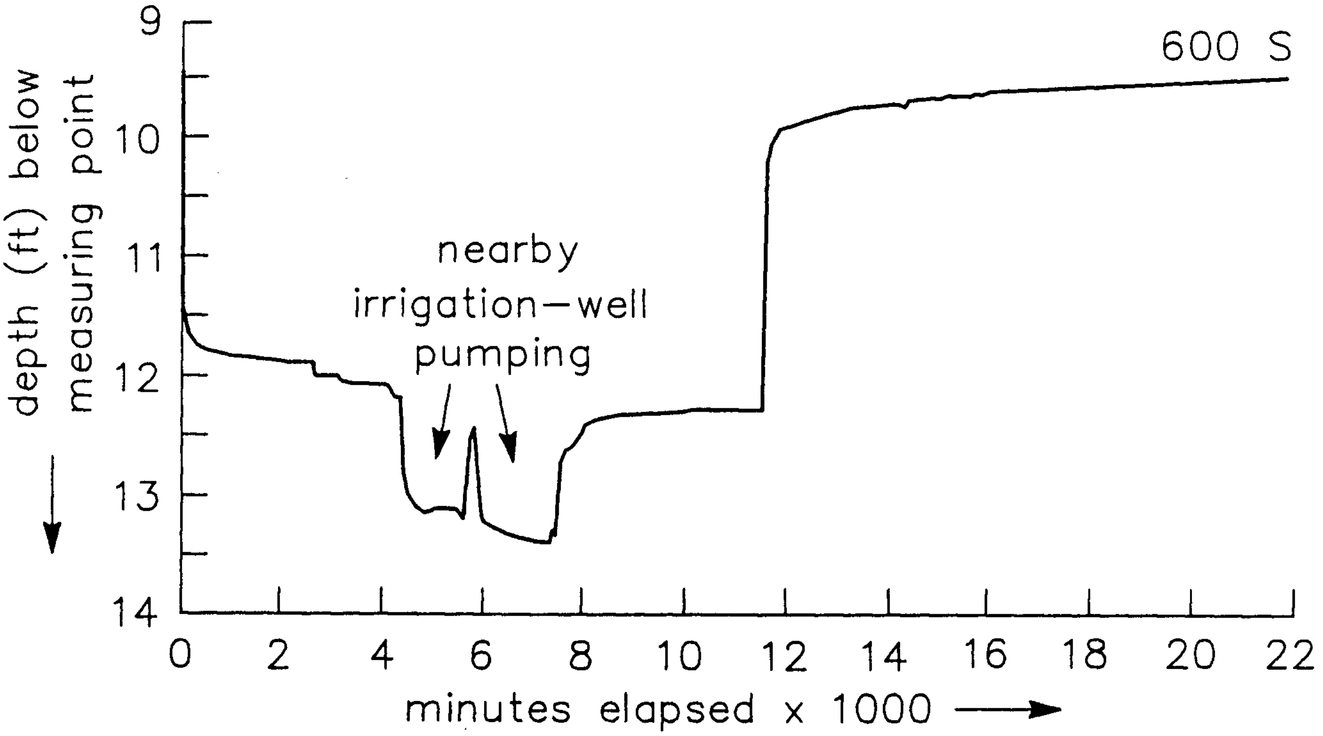

Figure 13. Drawdown recovery well hydrograph for the 600S observation well

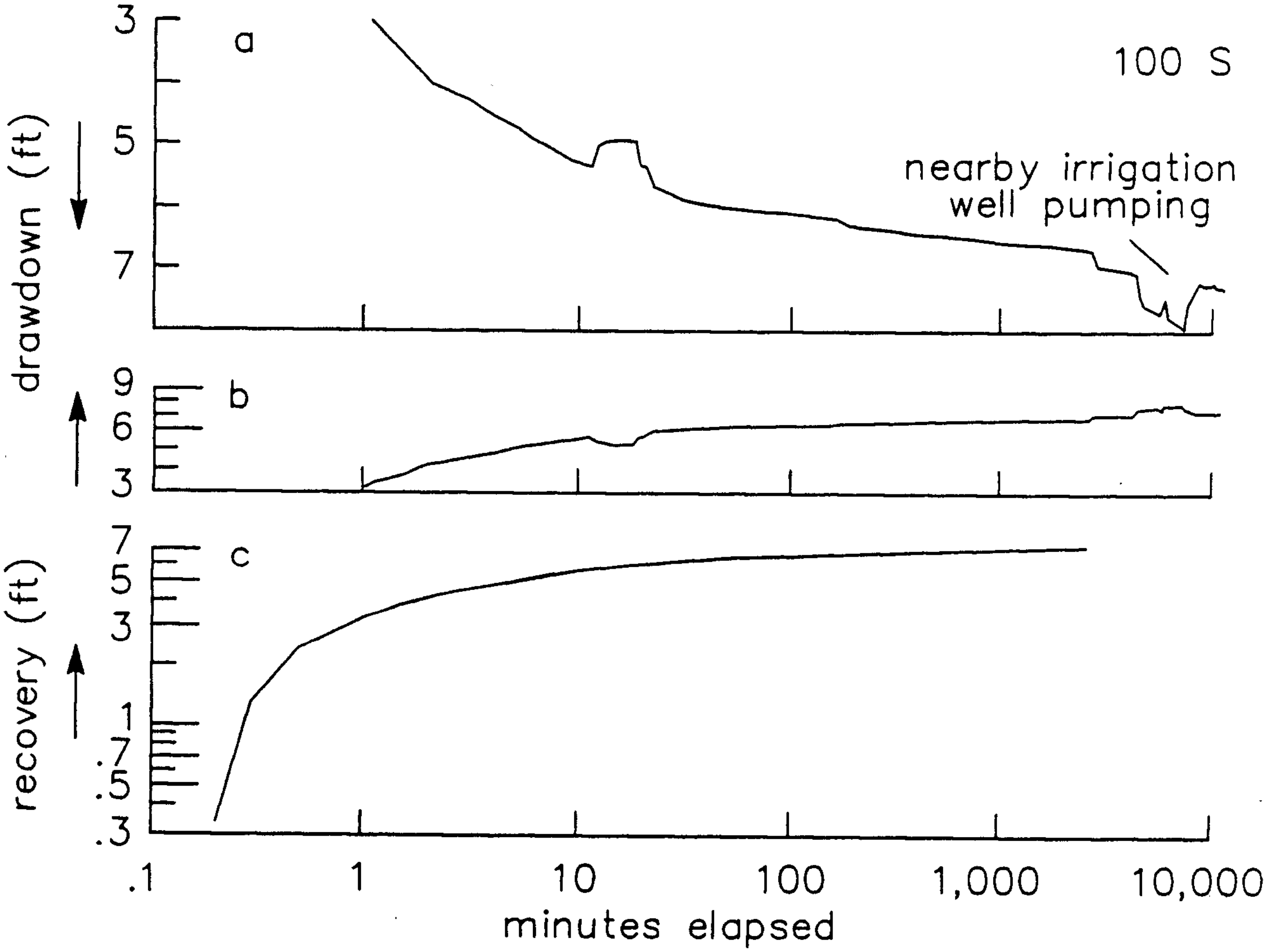

Figure 14. Semilog graph of drawdown hydrograph (a) and log-log graphs of drawdown (b) and recovery (c) hydrographs for the 100S observation well

measured data from various interpretive models are better emphasized. The effects of pump adjustments during the 10 to 20 minute interval, as well as the effects of nearby irrigation wells (Table 3) are clearly evident. Also, the flattening of the drawdown curve, especially prominent after the 10th-minute mark, is indicative of recharge and/or leakage effects which, however, have not completely stabilized the cone of depression. The cone of depression (Fig. 14a) is still continuously declining, albeit at a very slow rate due to the recharge/leakage effects. A log-log plot of the same 100S well hydrograph (Figure 14b) is nearly flat with the above-mentioned irrigation well interference effects and pump-adjustment effects subdued. The log-log recovery response (Figure 14c), like the arithmetic recovery response (Figure 13), shows a steep initial slope which flattens considerably after the first couple of minutes.

All above figures indicate that the aquifer is very transmissive as indicated by the extremely rapid recovery, the extremely rapid transmission of the pumping stress to the most distant wells, and the rapid flattening of the drawdown curve indicating ready transmission of recharge water to the cone of depression.

Figure 15 shows the resulting cone of depression on the southern side of the river on the morning (9:00 a.m.) of April 29, 1986, three hours before pump shut down. The detailed drawdowns at the pump-test site will be shown in the next figure. Note the steep gradients towards the stream, indicating a

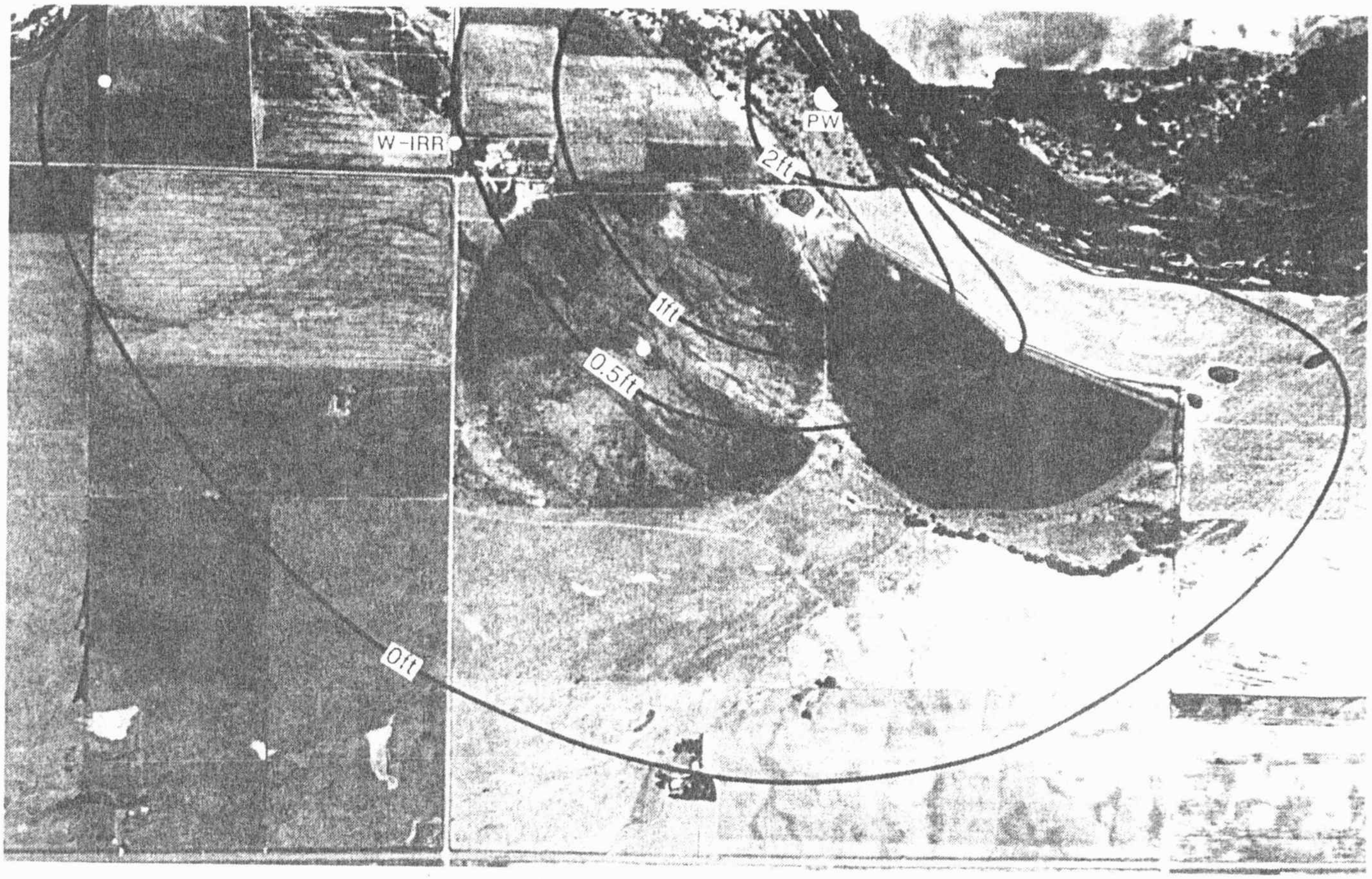

Figure 15. Cone of depression on the southwestern side of the Arkansas River on the morning of April 29, 1986. PW indicates the pumping well and W-IRR the west irrigation well

recharge source from the stream. Also, note the large area of influence of the pumping well with a radius of influence of at least 1.1 mile despite the presence of the stream. This corroborates the earlier inference that we are dealing with a very transmissive aquifer.

Figure 16 shows a detailed plot of the cone of depression at the stream-aquifer-test site during the same time as that of Figure 15. A quasi-elliptical shape of the cone of depression with the long axis approximately parallel to the stream is evident. Again, steeper gradients are developed northeast of the pumping well in the direction towards the river and flatter gradients are observed southwest of the pumping well in the direction away from the river, indicating the river is a recharge source.

A steep cone of depression, with a maximum drawdown of approximately 25 feet occurs in the immediate vicinity of the pumping well (Figure 16) and reduces to less than 9 feet approximately 50 feet away. Such a steep cone of depression, a profile of which is shown in Figure 17, is indicative of low storativity.

An interesting feature of the cone of depression, as shown in Figure 16, is that drawdown is observed on the opposite side of the river from the pumping well despite the highly permeable nature of the streambed, indicating that the stream was not acting as a constant head boundary. The observed drawdowns were relatively small close to the river, but they increased as one

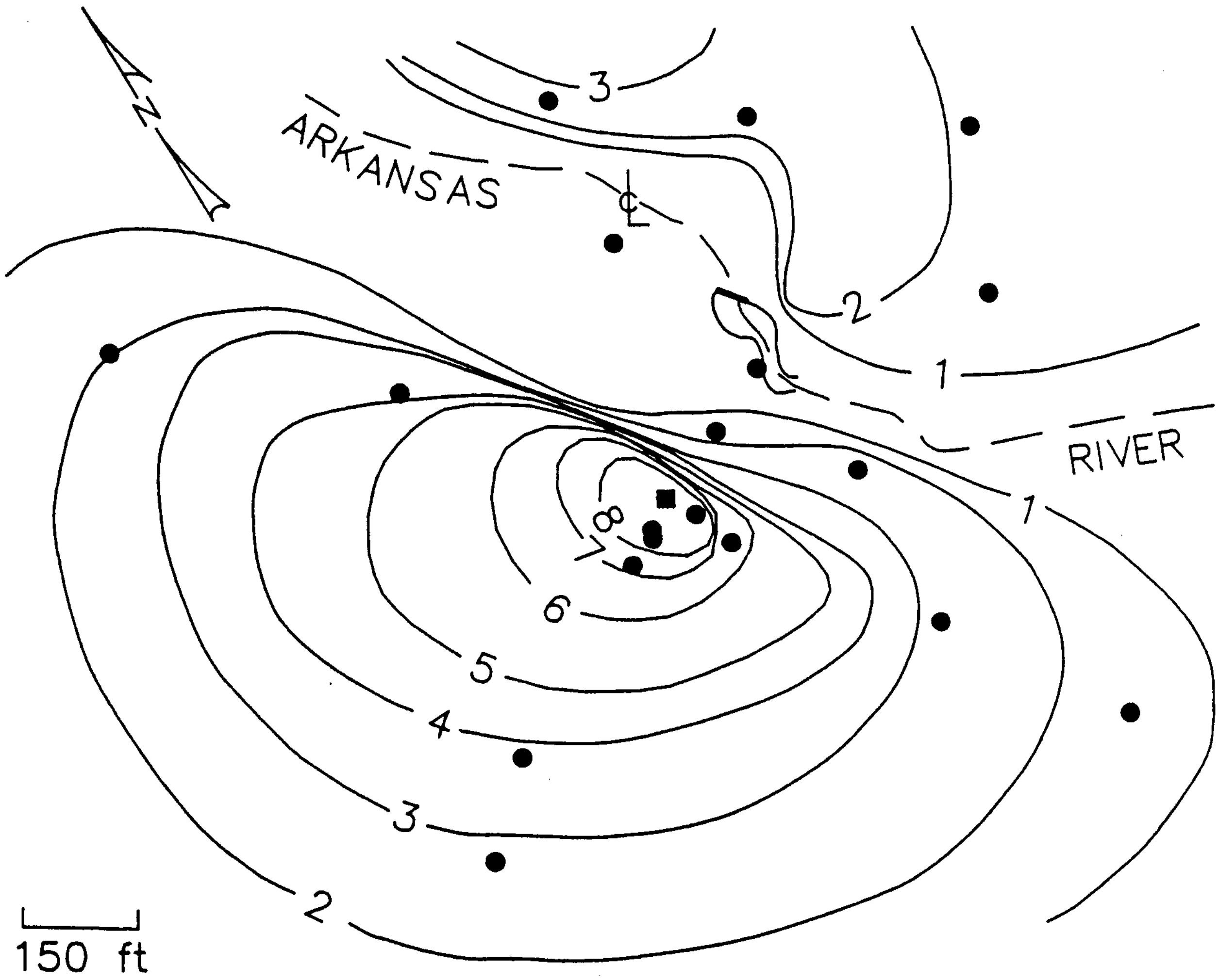

Figure 16. Cone of depression at the test site at the same time as that of Figure 15

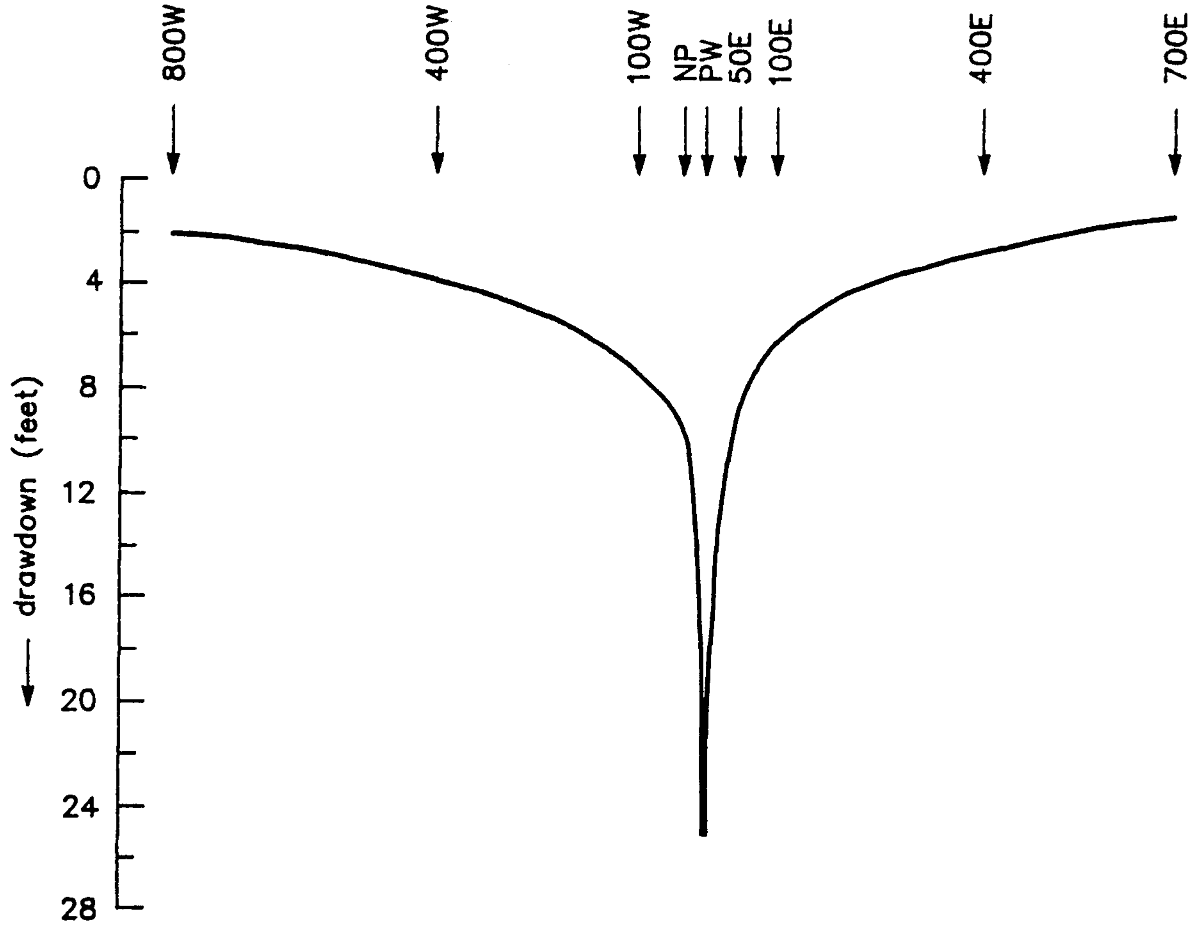

Figure 17. Profile of the cone of depression shown in Figure 15, approximately parallel to the Arkansas River

moved farther away from the river (Figure 16) to the stream side distant from the pumping well. A fundamental question to be asked, then, is why drawdown is observed on the other side of the river? This question will be dealt with later.

A typical response of the observation wells on the opposite, northeastern side of the river is exemplified by the semilog and plot of drawdown for the 600NW observation well (Fig. 18). Two facts from such well response are of significance. First, the effects of the pumping irrigation wells are felt on all wells on the other side of the river, reinforcing the previous observations of a highly transmissive aquifer. Second, the drawdown response of the north wells can be seen in the semilog plots, as exemplified by the 600NW well, as a flattening of slope indicating a recharge source. Another fundamental question to be asked is: why is a recharge source evident on the north wells? The obvious recharge source is the Arkansas River, and the pumping well on the southeastern side of the river is creating a sink towards which all water is directed, including water from the recharge source and water from the north side wells. This question will also be dealt with later.

From the responses of the observation wells (Figs. 13, 14 and 18), one can easily deduce that the aquifer response to the pumping well is not typical of water-table or unconfined aquifers, of which alluvial aquifers (such as the Arkansas River alluvial aquifer) are characteristic. No sigmoid drawdown curves with delayed drainage effects are observed, and no indications of

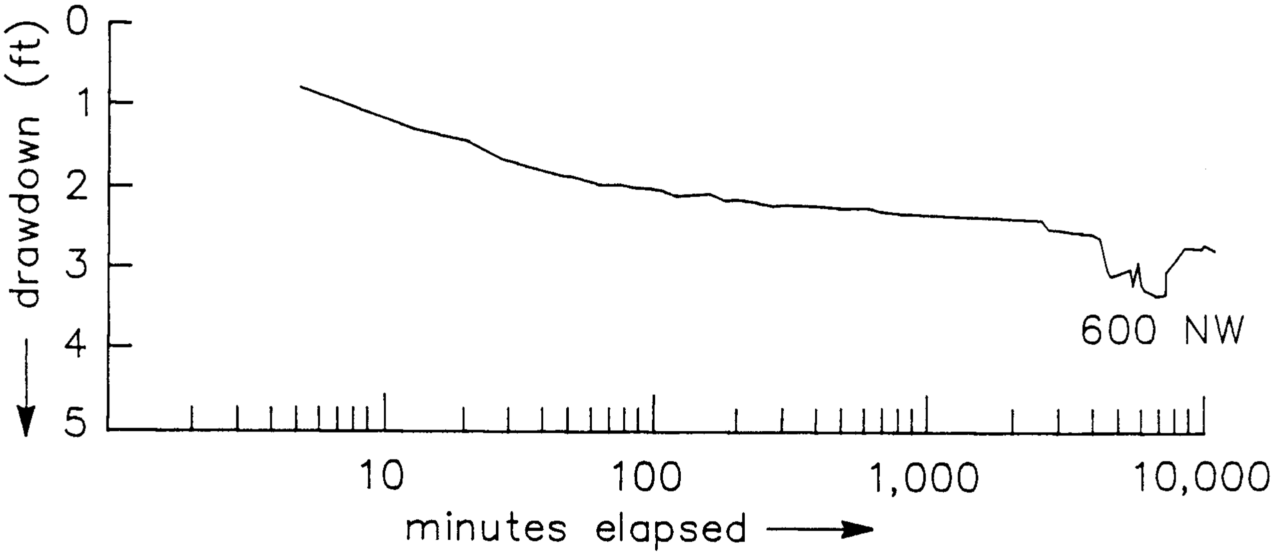

Figure 18. Semilogarithmic plot of drawdown hydrograph for the 600NW observation well

large storativities typical of unconfined aquifers are observed. One may, therefore, pose another fundamental set of questions: Why did the aquifer not exhibit a water table behavior, and why was "delayed" drainage response not observed?

In order to answer the above questions, the response of the overlying sediments and "dewatered" aquifer sediments will be examined to answer the last set of questions first.

Prior to and during the pumping and recovery phases, the water content of the overlying and dewatered aquifer sediments and the porosity of the aquifer were determined using a Campbell Pacific Nuclear (CPN) neutron probe. The neutron probe was operated continuously during the test, with detailed readings taken in the vicinity of the static water table and of the expected dewatered aquifer sediments. Figure 19 shows a neutron-based water content/porosity (if the sediments are water saturated) profile just before the pump test started and just before the pump was shut down for the recovery phase of the test. It is evident from the figure that despite an estimated drop in the water table of approximately 9 feet (Figure 17) at the neutron access tube locality (25 ft from the PW), the decrease in water content (dewatering) in the drawdown zone was minimal, with most of the dewatering occurring within one-half to one foot of the static water table (Figure 19). Some dewatering of the zone immediately above the water table (capillary fringe zone?) was also observed (Figure 19). The moisture contents were also monitored during recovery. Despite full water-table recovery,

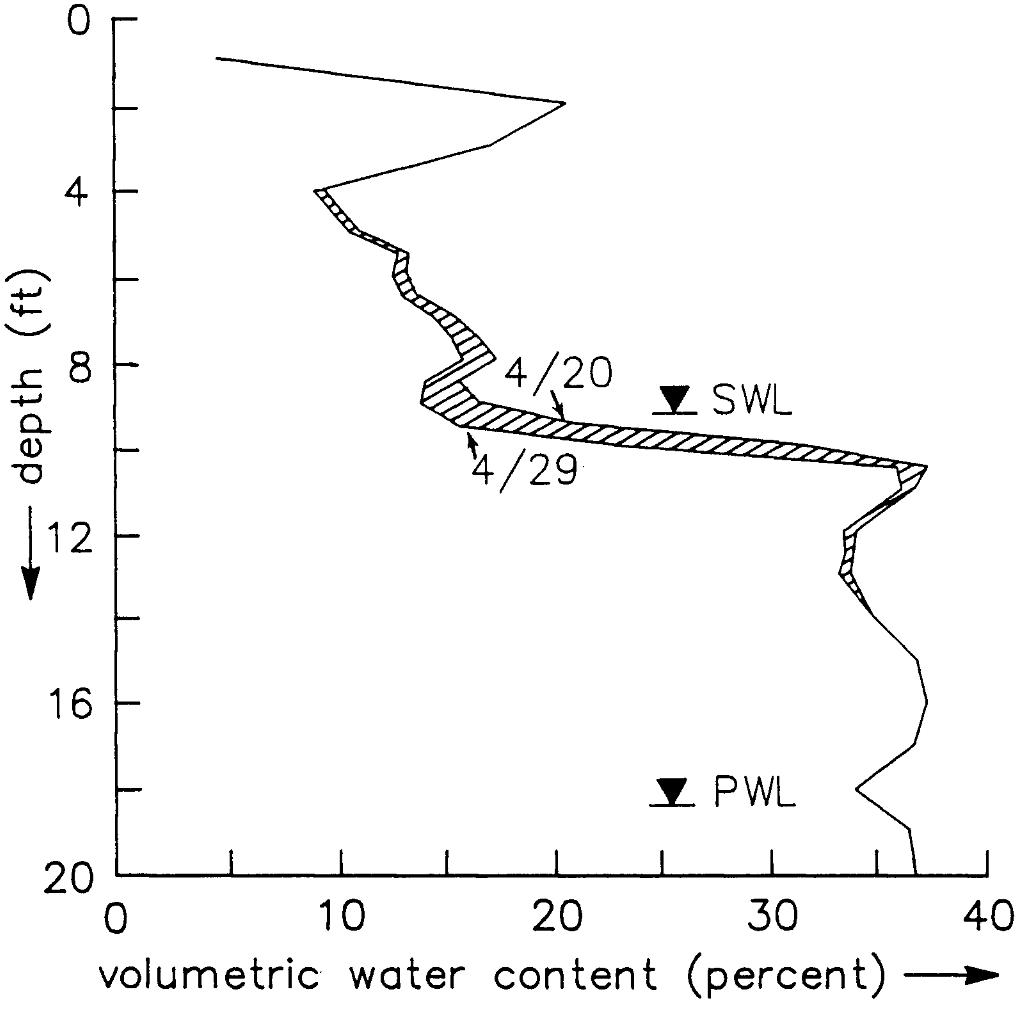

Figure 19. Volumetric water content vs. depth profiles of sediments near the pumping well immediately before pumping and at the maximum drawdown

moisture recovery was not complete by the end of the recovery period, probably due to the high water-level-recovery speed and the slow diffusion of entrapped air bubbles from the dewatered zone which was later resaturated.

To highlight these observations, a set of moisture-time patterns at different depths is plotted in Figure 20. It is evident from the figure that moistures started decreasing right after pumping started in the vicinity of the static water level, with the maximum dewatering observed at the 10-foot depth, where the static water level was located. Below the 11-foot depth, negligible amounts of dewatering were observed. The soil moistures started recovering right after the pump was shut off with the moisture recovery not completed even 3 weeks after complete water-level recovery (Figure 20).

The reason for no appreciable deep drainage in the vadose zone is due to the existence of a clay layer at a depth of approximately 30 to 40 feet (Figure 4), which was not penetrated by the cone of depression. The clay layer acted as a "leaky" seal holding the water content above it and effectively preventing dewatering of the sediments above it over the time scale of the test. Had the test continued for several weeks (or months), it is possible that delayed drainage effects would have been observed, especially after the cone of depression penetrated deeper than the level of the clay layer. The clay layer acted as an effective confining layer over the aquifer, causing it to behave as a confined, albeit leaky, aquifer and not as a

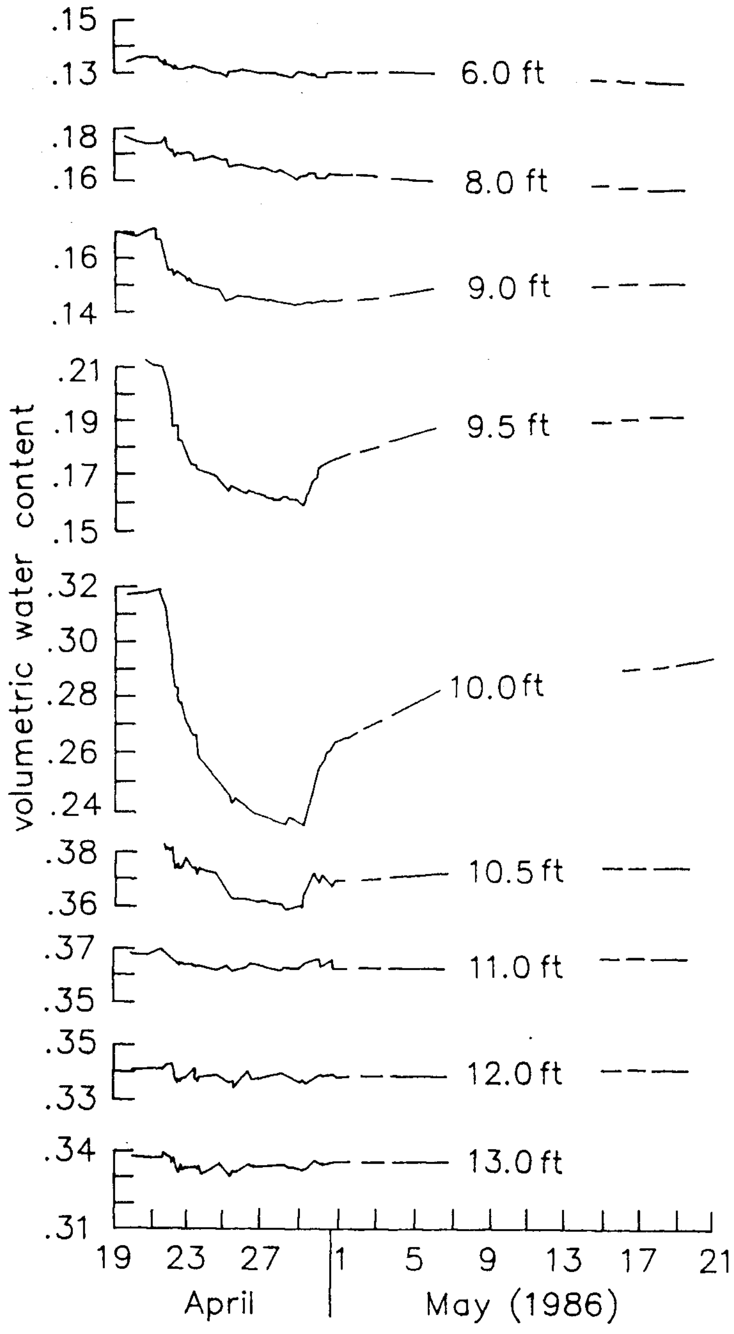

Figure 20. Sediment water content vs. time patterns for various depths during the drawdown and recovery phases of the test.

water-table aquifer. As mentioned in the geology section, this clay layer is widespread throughout the pump-test area and dips up toward the pumping well and the river (Figure 4).

As a consequence of the previously mentioned geologic information related to the semiconfining clay layer overlying the main aquifer and of the observation-well responses to pumping, a leaky confined-aquifer-analysis methodology was employed to analyze drawdown/recovery data. It should be noted that little difference exists between unconfined aquifer response, nonleaky confined aquifer response with a recharge source (image well) and leaky confined aquifer response over certain time intervals. All above mentioned analysis methodologies (Lohman, 1972) were employed on the observed data. However, the Hantush Jacob (1955) leaky confined aquifer methodology with no water storage effects from the semi pervious confining bed gave the best match to the observed data and the most consistent results. The Hantush (1960) modified theory of confined aquifers did not match most of the observed data.

All aquifer analysis methodologies employed in this study resulted in two groups of transmissivities. One group of wells consistently resulted in high transmissivities of the order of 400,000 gpd/ft. This group of wells includes predominantly the north wells, especially the 600N group (600NE, 600NC and 600 NW), the 400N and the 700E wells (Figure 2). It seems that an extremely high transmissive zone exists northeast and southeast of the pumping well crossing the Arkansas River. Most other wells resulted in a geometric mean transmissivity (T) of 145,150 gpd/ft, a mean storativity (S) of 5.6×10^{-4} and a mean leakage of 3×10^{-2} day^{-1}. Table 4 details the T, S, and K/b′ values for both drawdown and recovery analysis data and their appreciable deviations.

A distance-drawdown analysis of the data from the wells approximately parallel to the river did not result in a straight line which could be drawn with confidence. The resulting patterns, however, resembled the expected theoretical profiles for a stream aquifer system (Kazmann, 1948; Rorabaugh, 1956) as shown in Figure 21, indicating that recharge did occur from the river source. If recharge did not occur, the data should plot on a single curve, or on curves having similar shapes for cases with different transmissivities. The river-line curve in Figure 21 may not actually represent the main aquifer because the relatively shallow 100N and 200N well points did not penetrate the main aquifer.

Despite the above-mentioned reservations on fitting a straight line through the data on a semilog distance-drawdown plot, a straight line visual fit was attempted on the line of wells approximately parallel to the river (Figure 22). The resulting transmissivity value (T = 155,556 gpd/ft) is of the same order of magnitude as previously calculated. Although the hydraulic gradient along this line of wells may not be appreciably distorted because the effects of induced streambed infiltration on drawdowns are approximately equal at all wells

TABLE 4. HANTUSH-JACOB LEAKY CONFINED-AQUIFER-ANALYSIS RESULTS

Well I.D.	T (gpd/ft)	$\bar{T}$	$S \times 10^{-4}$	$\bar{S} \times 10^{-4}$	$\frac{K'}{b'} \times 10^{-2}$ (day^{-1})	$\overline{(\frac{K'}{b'})} \times 10^{-2}$
50S.D*	163,119	163,788	3.57	2.37	1.055	1.06
50S.R**	164,456		1.16		1.06	
100S.D	116,649	119,495	4.29	3.64	5.94	6.09
100S.R	122,340		2.98		6.23	
300SW.D	111,460	155,055	4.64	2.45	0.034	0.27
300SW.R	198,650		0.25		0.497	
300SE.D	146,450	154,125	0.66	1.90	3.5	3.7
300SE.R	161,800		3.14		3.9	
400S.D	100,318	100,318	7.84	5.06	2.9	2.9
400S.R	100,318		2.27		2.9	
600S.D	137,423	137,897	4.96	6.78	2.20	2.25
600S.R	138,370		8.60		2.23	
50E.D	94,196	97,257	16.6	10.55	24.9	25.7
50E.R	100,318		4.5		26.5	
100E.D	133,760	132,448	20.3	12.57	6.8	6.75
100E.R	133,135		4.84		6.7	
400E.D	157,982	179,310	8.23	6.25	4.6	3.8
400E.R	200,637		4.27		3.0	
100W.D	176,000	132,586	14.0	7.87	35.8	27.0
100W.R	89,172		1.73		18.2	
400W.D	211,197	207,965	3.73	3.93	0.76	0.73
400W.R	204,732		4.13		0.70	
800W.D	263,966	212,236	27.4	25.7	0.96	1.13
800W.R	160,510		24.0		1.30	
	Arithm. mean:	149,373		7.42		4.64
	Geometr. mean:	145,150		5.58		3.03
400N.D	385,840	420,917	5.95	4.67	1.08	0.7
400N.R	455,993		3.38		0.32	
600NC.D	401,274	386,412	5.26	4.65	0.76	0.73
600NC.R	371,550		4.04		0.70	
600NE.D	378,560	366,835	5.36	5.32	0.48	1.14
600NE.R	355,110		5.27		1.80	
600NW.D	393,406	393,406	3.08	3.08	0.65	0.65
700E.D	483,462	520,394	68.0	82.2	2.00	1.32
700E.R	557,325		96.3		0.63	
50SBR.R (bedrock OW)	71,656		1.26		0.56	

* Drawdown
** Recovery

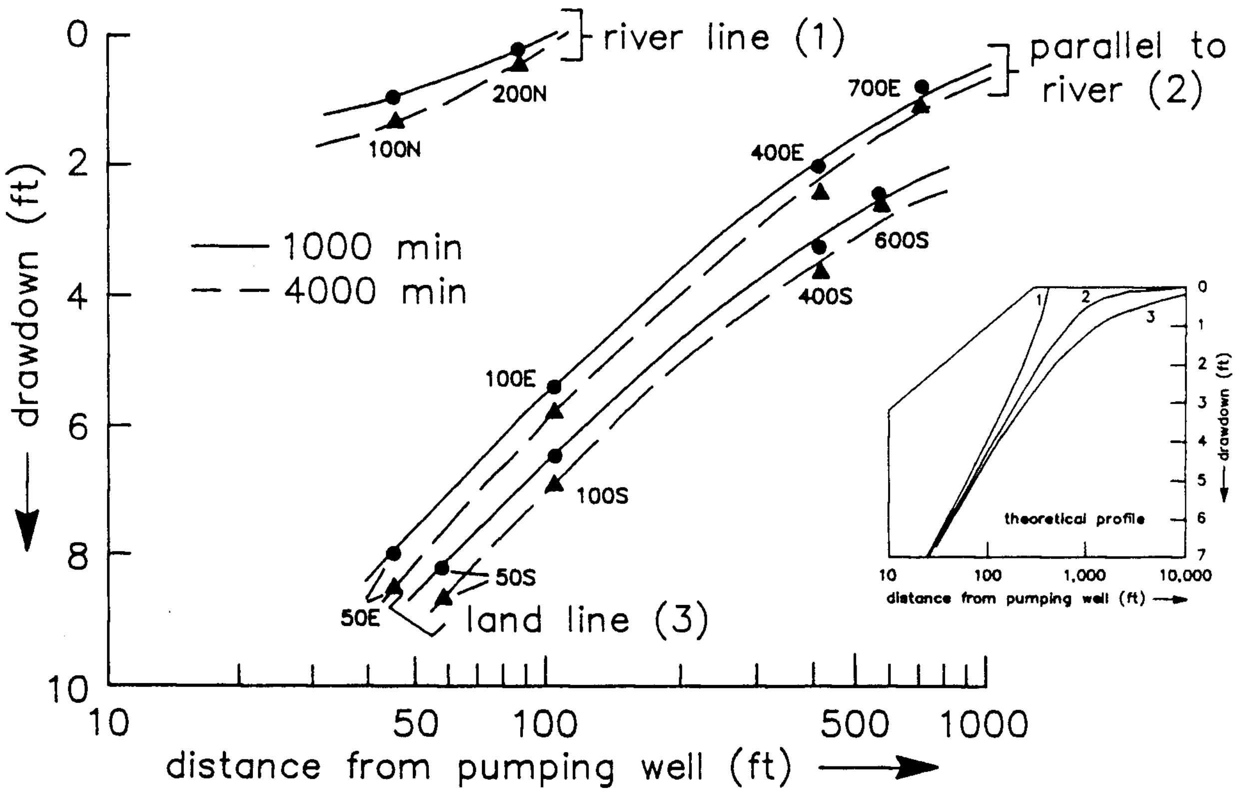

Figure 21. Semilogarithmic distance vs. drawdown plot for various lines of wells approximately parallel (2) or perpendicular (1 and 3) to the Arkansas River. Theoretical distance-drawdown diagram adapted from Rorabaugh (1956)

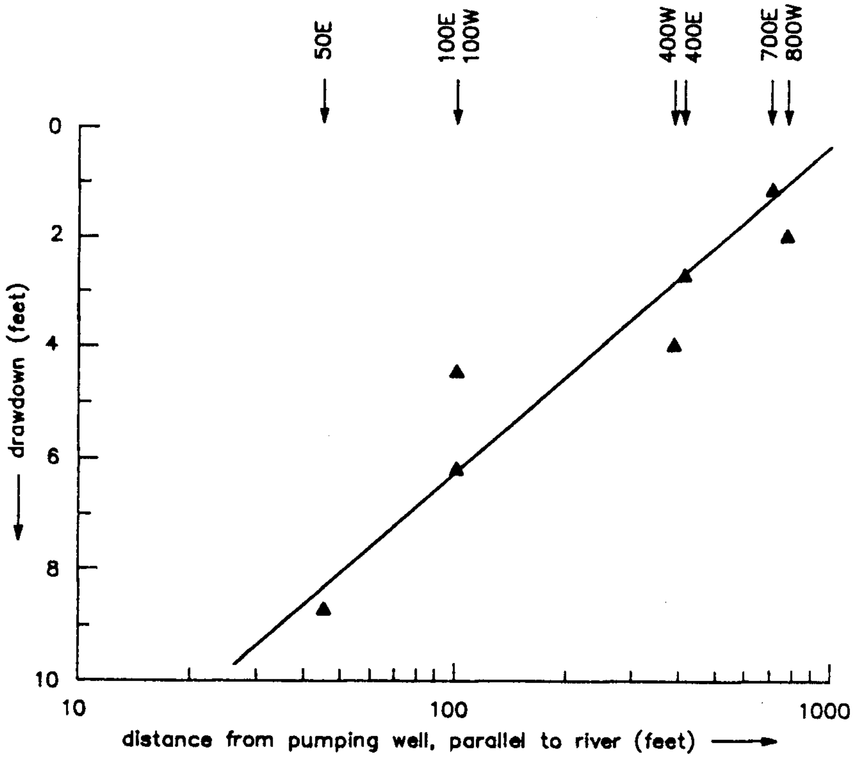

Figure 22. Straight-line eye-fit through observed data (t -10,000 min) plotted on distance-drawdown semilog graph for the line of wells approximately parallel to the Arkansas River

parallel to the river, the total values of drawdown in the observation wells are much less than they would be under infinite aquifer conditions without a recharge boundary. Therefore, the aquifer storativity cannot be determined from the distance-drawdown graph.

To answer the first-posed question as to why drawdown was observed on the north side of the river, one should examine the geology and screen-interval locations of the pumping and observation wells. It can be seen from Figure 4 that the semiconfining clay layer becomes shallower closer to the Arkansas River. When installing well-point 200N in the immediate vicinity of the river, a clay layer was encountered at approximately 10 feet from the surface. The clay layer also is present at varying depths on the distant side of the river. It should also be noted that all 2- and 5-inch observation wells, as well as the pumping well, are screened consistently below the semiconfining clay layer (Figure 4). The combination of the semiconfining layer and the screen locations could explain why the north wells responded to the distant irrigation-well pumping as indicated in Figure 18. In other words, only the semiconfined lower aquifer, which probably extends beneath the Arkansas River and beyond, is the stressed and monitored entity. The fact that the 100NW and partially the 100N well points, as well as the 200N well point, did not penetrate the confining clay layer, resulted in minimal drawdowns in these wells and barely noticeable effects by the distant irrigation-well pumping (Figure 23). Nearby well points, however, which either penetrated or did not encounter the clay layer because of some clay-layer discontinuities, exhibited larger drawdowns and showed the effects of distant pumping (Figure 24). Thus, the semiconfining clay layer acted as a partial seal, creating a "perched-type water-table" condition. This explains why near the stream, with the source of water and resulting induced infiltration, drawdowns were minimal; while further away from the stream and the pumping well, larger drawdowns were observed. These observations also possibly explain why the Hantush-Jacob leaky confined-aquifer analysis is applicable: negligible drawdown was observed on the water-table aquifer above the confined aquifer, and also negligible storage effects were expected from the confining layer because of its small thickness (generally less than 10 feet thick) and its partial continuity.

It is interesting to note that of all observation wells, only two did not exhibit a significant recharge effect. Both of these (Figures 23a and 23b) were well points completed within the clay layer, which acted as a partial "barrier boundary" to negate the "recharge boundary" effect.

Given the above explanation of observed drawdowns on the distant side of the river, it would be expected that the induced infiltration through the river bed and the leakage through the semiconfining clay layer would be diverted towards the pumping well, and therefore continued drawdown would be expected in the north wells until a steady-state condition is achieved. Under

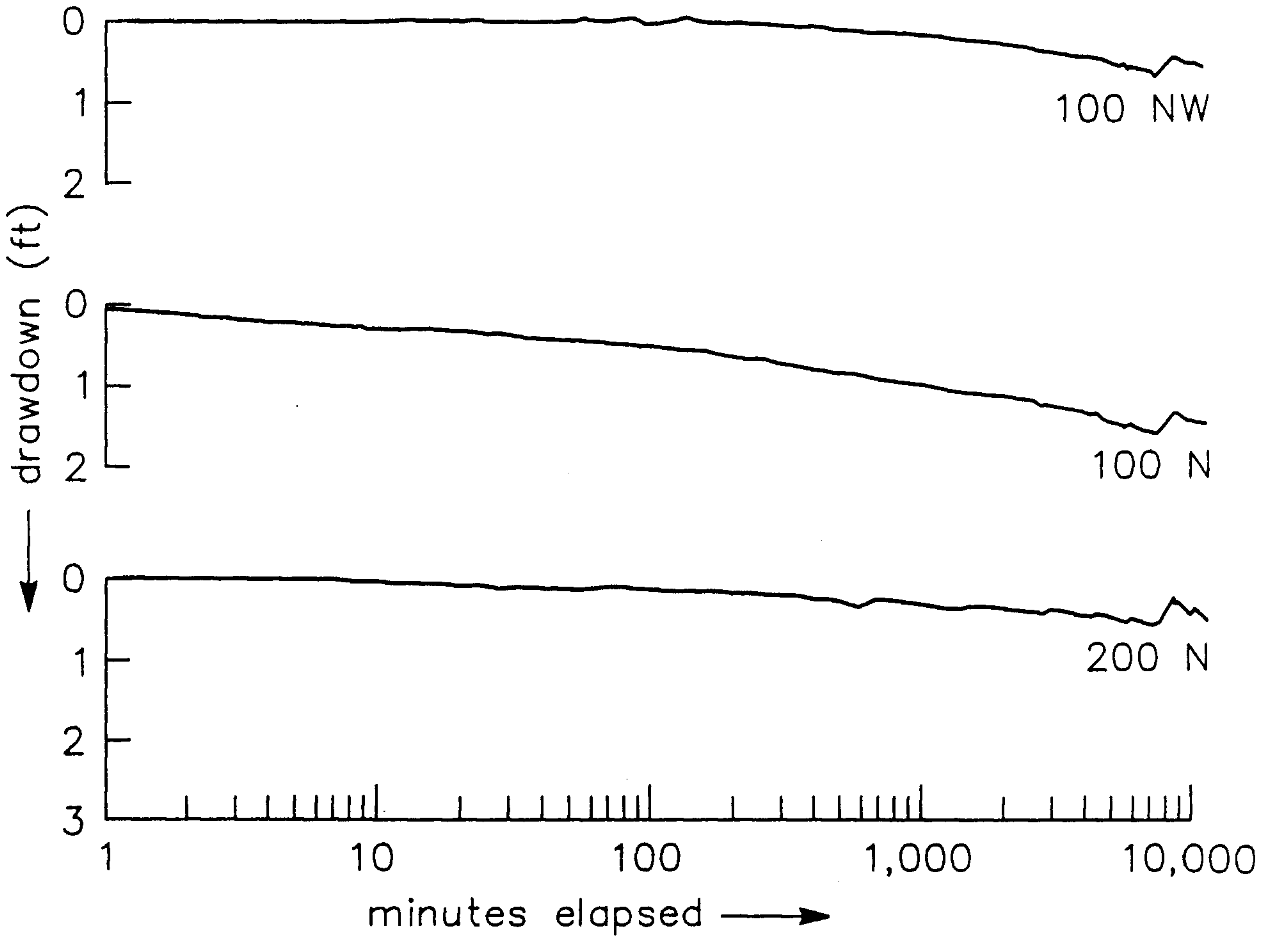

Figure 23. Semilogarithmic drawdown hydrographs for the 100NW, 100N and 200N observation wells

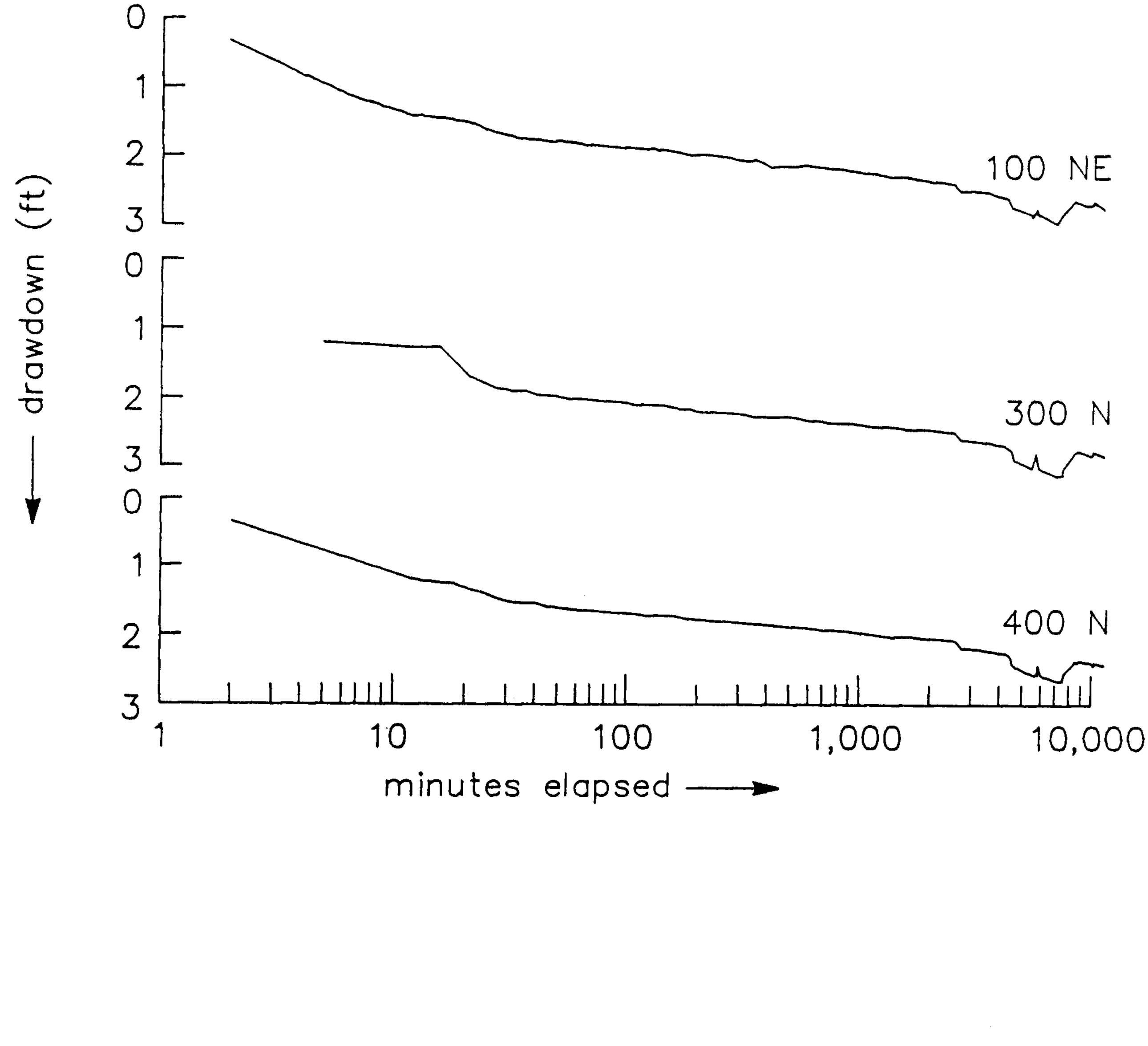

Figure 24. Semilogarithmic drawdown hydrographs for the 100NE, 300N and 400N observation wells

the steady-state condition, the induced infiltration and leakage waters effectively balance out the pumped water. However, the north wells show a flattening of the semilogarithmic time-drawdown curve (Figures 18 and 24), indicating a source of recharge. Although this could be interpreted as a leakage effect, a more likely explanation is a combination of both leakage and a recharge source from Walnut Creek, some 3100 feet north and northeast of the pumped well (Figure 1).

Figure 25 represents the water-level elevations during pumping after 8 hours of continuing pumping (21:00 hour, April 21, 1986). Two important features can be seen: (1) A more highly transmissive path from the northeast, consistent with the high-transmissivity layer encountered in the 600N group of wells more than one mile away. Water chemistry data discussed in the chemistry section further support the Walnut Creek source of recharge. (2) The steep hydraulic gradients along the line of 100N and 100NW wells indicate that the clay layer is acting as a partial barrier to flow from the northeast, thus emphasizing the highly transmissive paths to the northeast and southeast.

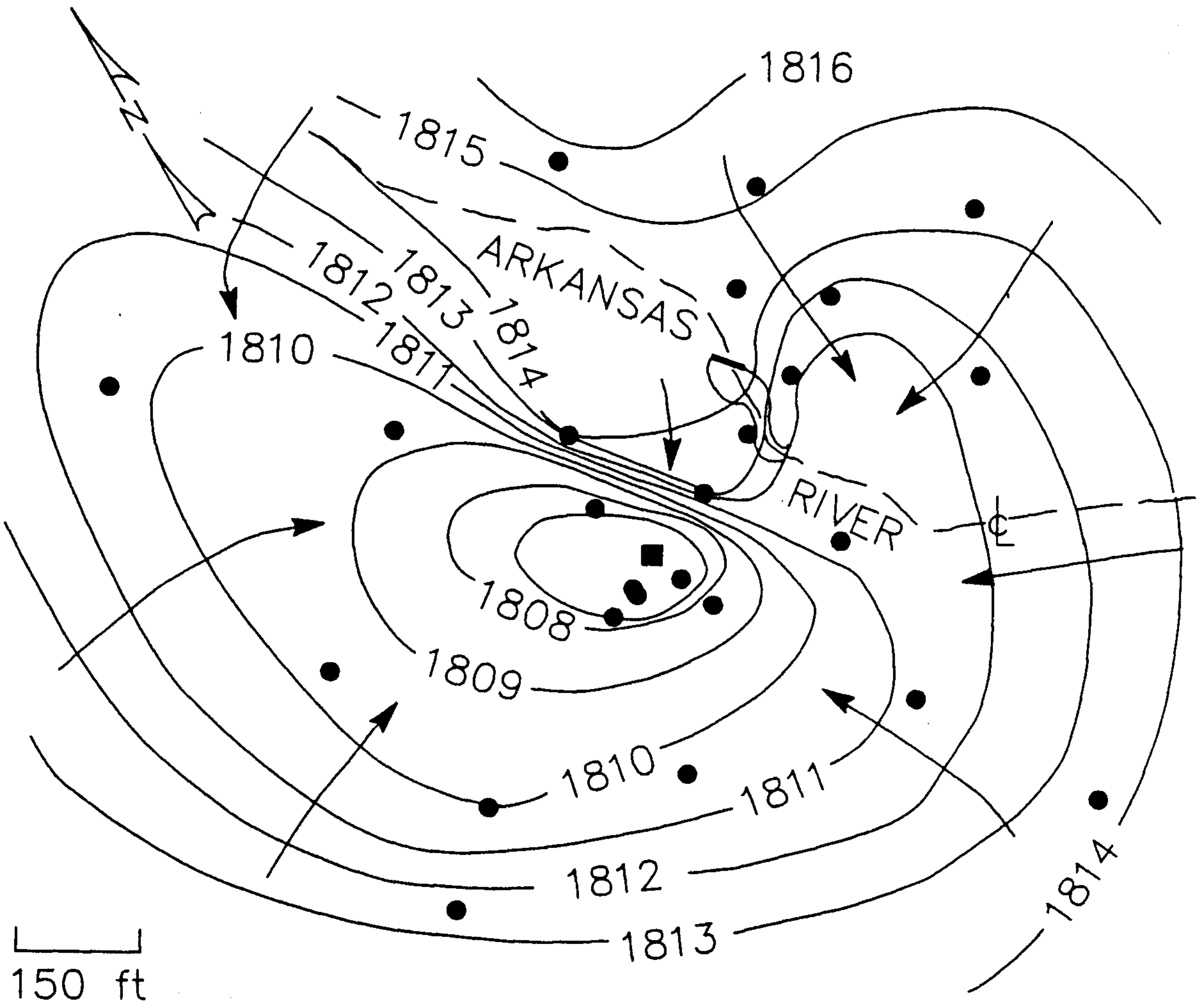

Figure 25. Water-level elevation contours at the test site after 8 hours of continuous pumping

DISTANCE-TO-SOURCE ANALYSIS

Rorabaugh (1956) developed a number of equations for calculating the distance **a** to the line source given that drawdowns, s, at any two observation wells (OW) at known distances, r, from the pumped well (PW) and of different configurations relative to the line source, are known. These equations are based on the following assumptions: homogeneous (nonleaky) confined aquifer of infinite extent, in which pumping has continued long enough to establish equilibrium or steady-flow conditions. Also, barometric pressure and river elevation remain constant, and the temperature of the river water and water in the aquifer are equal and remain constant. Rorabaugh's equations shown in Table 5, column (a) are rearranged for iterative (trial-and-error) calculations in column (b).

If various pairs of wells are used and values of **a** are consistent, the assumed conditions are verified. However, if the assumed conditions are valid and values of **a** differ, the transmissivity may not be uniform. Other graphical and analytical methods exist for determining values of **a** (Kazmann, 1946, 1948; Heath and Trainer, 1981; Hantush, 1959, 1965). Although probably none of these were applicable to the data from this test (all above-mentioned methods were attempted), Kazmann's method (1948) relying exclusively on the river line of wells, was employed because of its simplicity (Figure 21) resulting in a distance of the line source, **a** = 110 ft.

TABLE 5
RORABAUGH'S (1956) EQUATIONS FOR CALCULATING THE DISTANCE a TO A LINE SOURCE

	(a)	(b)
Pair of OW on line perpendicular to river on river side of PW	$\frac{s_1}{s_2} = \frac{\log \frac{2a-r_1}{r_1}}{\log \frac{2a-r_2}{r_2}}$	$a_j = \frac{1}{2} \ (2a_i-r_2)^k \ (\frac{r_1}{r_2^{\ k}}) + \frac{r_1}{2}$
Pair of OW on line perpendicular to river on land line (side of PW away from river)	$\frac{s_1}{s_2} = \frac{\log \frac{2a+r_1}{r_1}}{\log \frac{2a+r_2}{r_2}}$	$a_j = \frac{1}{2} \ (2a_i+r_2)^k \ (\frac{r_1}{r_2^{\ k}}) - \frac{r_1}{2}$
Pair of OW on line through PW parallel to river	$\frac{s_1}{s_2} = \frac{\log \frac{\sqrt{(4a^2+r_1^{\ 2})}}{r_1}}{\log \frac{\sqrt{(4a^2+r_2^{\ 2})}}{r_2}}$	$a_j = \sqrt{[\frac{1}{4} \ (4a_i^2 + r_2^{\ 2})^k \ (\frac{r_1}{r_2^{\ k}})^2 - \frac{r_1}{4}]}$

$k = s_1/s_2$ (drawdown ratio). Assume a_i and obtain a_j. Solution obtained when $a_j = a_i$ within an error tolerance.

Iterative application of the formulas in column (b) of Table 5 for selected pairs of wells using drawdown values near the end of the test (where near steady-state conditions may be assumed) resulted in the distance values to the line source shown in Table 6. Values of drawdowns in observation wells for these calculations were taken near the end of the pumping phase.

TABLE 6. DISTANCE-TO-LINE-SOURCE VALUES CALCULATED FROM RORABAUGH'S (1956) EQUATIONS

Well pair	Calculated a (ft)
400W-800W	480
100W-400W	790
50E-100E	380
100E-400E	580
50S-100S	505
100S-400S	560
100N-200N	272

The variability in calculated **a** values shown in Table 6 indicates that the already-mentioned assumptions on which these formulas are based are not entirely validated. However, the differences in calculated **a** are not extreme, with a resulting average or effective **a** ≃ 510 ft, possibly indicating the existence of not only the Arkansas River source, but also of an additional source of water at some farther distance away (Walnut Creek). The calculated distance to source based on the "river line", using either the Rorabaugh (**a** = 272 ft) or Kazmann (**a** = 110 ft) methods are of the correct order of magnitude, with the actual distance to the Arkansas River (**a** = 210 ft) being the approximate average of these two estimates.

Knowing the effective distance to the line source **a**, the aquifer transmissivity (T) can be computed on the basis of drawdown at each observation well (Rorabaugh, 1956). Also, knowing **a** and T, the aquifer storativity can be determine through a trial-and-error procedure (Walton, 1964). All these relationships are based on the assumptions stated at the beginning of this section.

In order to check the plausibility of the derived hydrogeologic constants, the above-mentioned equations for T and S estimation based on knowing **a** and s, were applied to the field data under the assumption that all leakage is lumped into induced infiltration from a line source. The results agreed closely with the estimated values.

INDUCED INFILTRATION AND SDF ANALYSIS

Streambed Hydraulic Conductivity

The vertical conductivity of the streambed sediments was determined at two places near the central stream-gaging station which is located in a straight line to the stream directly northeast of the pumping well (Figure 2). An infiltrometer consisting of thin-wall galvanized-steel 8-inch-diameter tube was inserted into the sediments to a depth of less than one foot, the tube was filled with water to a depth well above the stream stage, and the rate at which the water level declined inside the infiltrometer was monitored through a type F Stevens recorder set to a 12-hr quartz clock position. The stream level was also monitored by another recorder. Using the variable-head equation (see, for example, Heath and Trainer, 1981), the streambed hydraulic conductivity of the first test (May 7, 1986) resulted in K = 203 gpd/ft^2 (27.2 ft/day or 1.13 ft/hr) while the second test (May 28, 1986) resulted in K = 153 gpd/ft^2 (20.4 ft/day or 0.85 ft/hr). The in-place infiltrometer results are satisfactorily consistent, given the high field-K variability of sediments.

The average hydraulic conductivity of the streambed sediments for the reach between the central and downstream streamgaging sites was also computed using Darcy's law. This law states that the hydraulic conductivity of a material, K, is equal to the discharge through the material, Q, divided by the area, A, through which the flow is occurring and by the hydraulic gradient, i, [K = q/(A . i)]. The discharge or downward flow was considered to be equal to the average stream-flow depletion measured in the study reach after the pumping well was turned on (0.45 cfs = 202 gpm). The streambed area for the reach (A = 12,600 ft^2) was determined by multiplying the measured streamline length of the reach (700 ft) by the average width of the stream (18 ft). The average hydraulic gradient during the pump test between the 2-feet and 3-feet-deep minipiezometers at the stream bottom at the central streamgaging site (0.05 ft/ft) was taken as the effective hydraulic gradient. The resulting hydraulic conductivity was thus estimated as K = 57.6 ft/day = 431 gpd/ft^2, which is of the same order of magnitude as the infiltrometer estimates, although a higher value. All the above-calculated streambed hydraulic-conductivity values are much smaller than the estimated aquifer hydraulic conductivity K = T/b = (19,405 ft^2/day)/68 ft = 285 ft/day = 2,135 gpd/ft^2, with the saturated thickness, b, taken as that below the confining clay layer. If a unit hydraulic gradient for the streambed sediments is assumed, then K = 22 gpd/ft^2, which is one order of magnitude less than the measured infiltrometer values, and two orders of magnitude less than the calculated aquifer hydraulic conductivity.

Induced Infiltration and Streamflow Depletion

A number of analytical streamflow depletion models are increasingly being used for purposes of water rights administration in several western states. However, there have been no adequate field studies of the hydrologic properties of stream-bottom sediments and of the effects of pumping on aquifer hydrodynamics very close to streams in order to assess the limitations of simplifying assumptions in analytical equations or to verify the predictive capabilities of stream-aquifer numerical models. Theis (1941) developed an equation to estimate streamflow depletion caused by pumping wells at different distances from the stream. The equation is based on the assumption that the aquifer is under nonleaky confined conditions, is homogeneous and isotropic, and extends to infinity away from the stream. The equation also assumes that the stream completely penetrates the aquifer and is straight and infinite in extent. Glover (1952), Glover and Balmer (1954), and Glover (1974) built upon Theis' (1941) solution so that the length of the stream stretch from which various percentages of the well flow are derived can be easily calculated.

Values for streamflow depletion at the pump-test site due to pumping were computed from the Glover equation (1952; see also Maasland and Bittinger, 1963) shown in equation (1) below

$$\frac{q_{\Delta L}}{Q} = \frac{1}{2\pi} \int_0^{\alpha} \frac{e^{-k_1(1+\alpha^2)}}{(1+\alpha^2)} \, d\alpha \qquad (1)$$

Where $k_1 = a^2/[4(T/S)^2 t]$, and $\alpha = \Delta L/\mathbf{a}$; **a** is the perpendicular distance from the pumping well to the stream; $q_{\Delta L}$ is the flow of the well drawn from the stream-reach length ΔL, whose origin is the intersection of the distance **a** with the stream bank; Q is the well discharge (pumpage), S is storativity, T is transmissivity, and t is the time since the pumping stress commenced. Equation (1) was compared to the measured values to determine the validity of the equation in predicting streamflow depletion (Figure 26). For the computations, the actual distance to the stream was used, i.e. $\mathbf{a} = 210$ ft; $T/S = 3.465 \times 10^7$ ft^2/day and $\alpha = \Delta L/\mathbf{a} = 700/210 = 3.33$. Comparison of these values indicates that the depletion of flow between the central and downstream gaging sites was appreciably less than the computed depletion. The partially penetrating nature of the stream and the fact that most of the water moving from the stream toward the well had to move vertically downward through the less-permeable clay layer, which was semi-confining the main aquifer, are the apparent reasons for the observed discrepancies.

Jenkins (1970) presented dimensionless tables and curves for computing streamflow depletion caused by pumping a well. The equation used by Jenkins to compute the streamflow-depletion rate is

$$q/Q = \operatorname{erfc} \sqrt{(\frac{sdf}{4t})} \qquad (2)$$

where the stream depletion factor (sdf) is defined as $(\mathbf{a}^2 S)/T$,

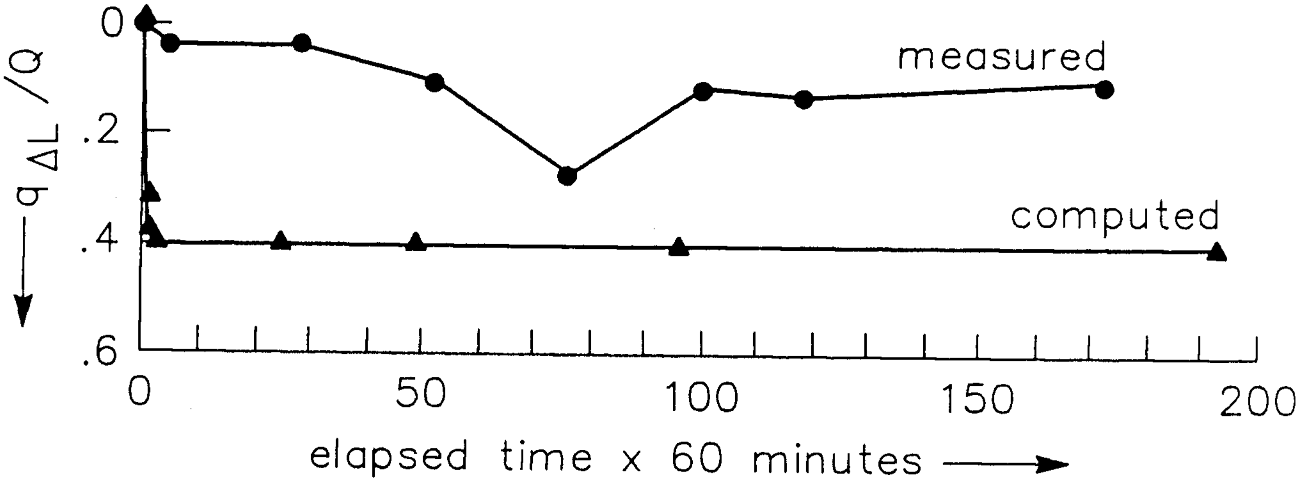

Figure 26. Comparison of measured and computed streamflow depletion for the Arkansas River reach length, ΔL, between the central and downstream gaging stations based on Glover's (1952) equation

q is the stream depletion caused by the discharging well pumping at a rate of flow Q, and erfc is the complementary error function.

Jenkins' curve relating q/Q to t/sdf on log-log paper is conveniently replotted on semilog paper here (Figure 27). Employing this curve and using our pump-test-analysis values with sdf = 1.27×10^{-3} day (using the actual distance to the stream), or with sdf = 7.5×10^{-3} day (using the computed effective **a** = 510 ft), results in the streamflow depletion rate as a function of time depicted in Figure 28. This figure shows that within a very short time after pumping started (in the order of very few minutes), a substantial proportion of pumpage (more than 80 percent) was being supplied by the stream.

Glover's (1974) stream-aquifer analysis allows one to estimate the reach of the river, centered on the perpendicular distance to the stream from the pumping well, which supplies various percentages of the flow of the pumping well, provided steady-state conditions are achieved. Under these conditions, the flow from the linear reach -x to +x is given by

$$\int_{-x}^{+x} f\,dx = \frac{2Q}{\pi} \arctan \frac{(x)}{\mathbf{a}} \qquad (3)$$

where f is the flow per unit length of the streambank. Thus, for example, one half of the flow of the well will come from a linear reach of the river 2**a** long centered on the well, and over 70 percent of the well flow will be supplied by a similar reach 4**a**

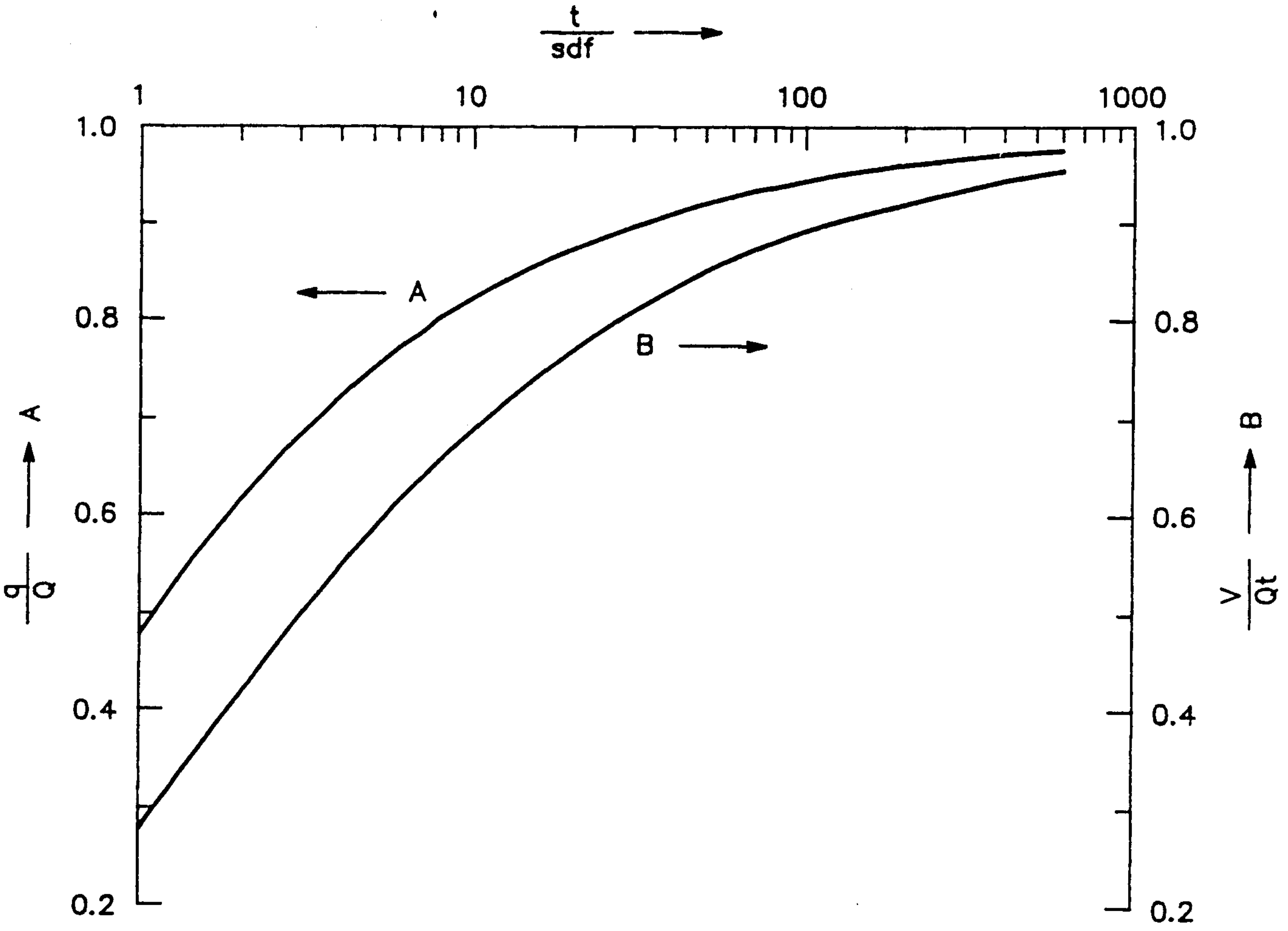

Figure 27. Semilogarithmic curve relating streamflow depletion to the sdf factor adapted from Jenkins (1970)

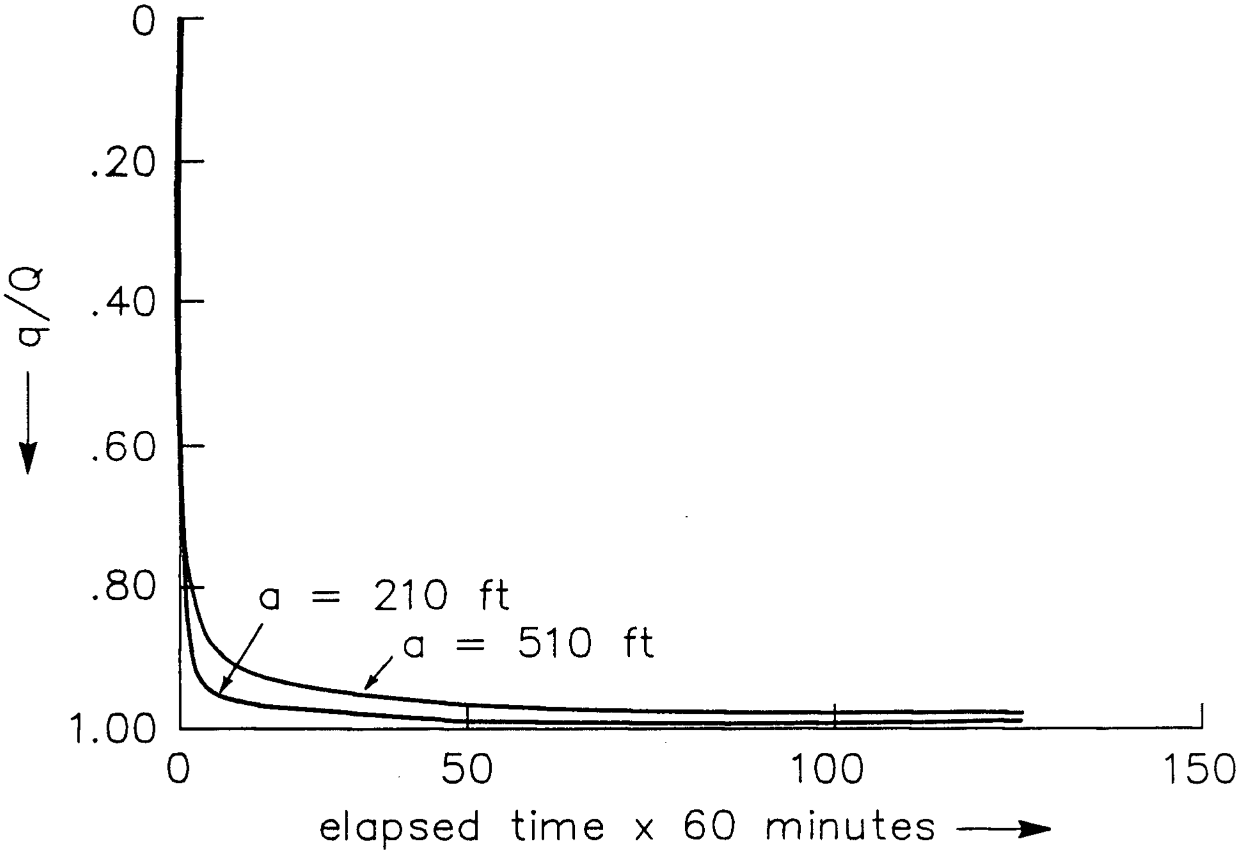

Figure 28. Streamflow depletion rate of the Arkansas River at the test site based on Jenkins' (1970) equation

long. Consequently, more than 90 percent of the well flow will be supplied by a river reach 13**a** long centered on the well. Using the actual distance to the Arkansas River (**a** = 210 ft), this translates to a 2,730-ft-long linear reach. Using this river length as the effective stream source supplying the pumping well and assuming that the average measured streamflow loss between the central and downstream gaging stations (0.45 cfs/700 ft reach) is representative of the induced infiltration over the estimated entire effectively contributing river length (2,730 ft), the equation results in a total induced infiltration amount of 1.76 cfs. (It should be noted that this is probably an overestimated amount because the measured river reach is closest to the pumping well). Given that the amount of pumpage was 1,750 gpm or 3.9 cfs, the ratio of streamflow depletion to the quantity of water pumped is q/Q = 3.5/3.9 = 45 percent, which is considerably less than the percentages derived from the sdf analysis (Figure 28). Also if the measured average ground-water contribution to streamflow (baseflow rate) over the stream reach between the central- and downstream-gaging stations (0.22 cfs/700 ft reach) is extended over the estimated effectively contributing river length of 2,730 ft, then this stream baseflow would amount to 0.86 cfs, which is close to half the amount of induced infiltration.

WATER CHEMISTRY AND RELATED STATISTICS

Ground water at the pump-test sites can be classified into three groups based on the greatest percent of chemical constituents (Figures 29 and 30; Hem, 1985):

Calcium-sodium-sulfate-bicarbonate facies: 700E, 800W, 600NC, 600NW, 600S, 400W and 600S.

Calcium-sodium-bicarbonate facies: 100E, 100W, 100S, 300SW, 300SE, 50E, 50S, 400S, 600NE and the pumping well.

Sodium-chloride facies: 50S-BR.

An overall view of the chemical quality of water at the study area, shown in Figure 31, indicates a noticeable variation throughout the site.

Selected water samples for chemical analysis were collected prior to, during, and after the eight-day pumping test. The most marked changes in chemistry were noted in the pumping well: Ca, Mg, Na, SO_4, Cl, NO_3, and conductivity increased over time. As shown on trilinear diagram (Figure 32), water quality in the pumping well changed from its original composition and moved toward the more saline water end of the diagram. This suggests that mixing with poorer quality waters may have caused the decline in the pumping well-water quality.

Two possible sources for poorer quality water exist: the Arkansas River and the bedrock aquifer (Figure 32). Both types of waters have conductivities greater than 1,400 μmhos/cm. The bedrock water can probably be eliminated due to its very low concentrations of nitrate (0.1 mg/L). Although there is significant rise in the sulfate and chloride concentrations in the pumping well during the test, neither constituent (in particular the chloride concentration) shows enough of a jump to

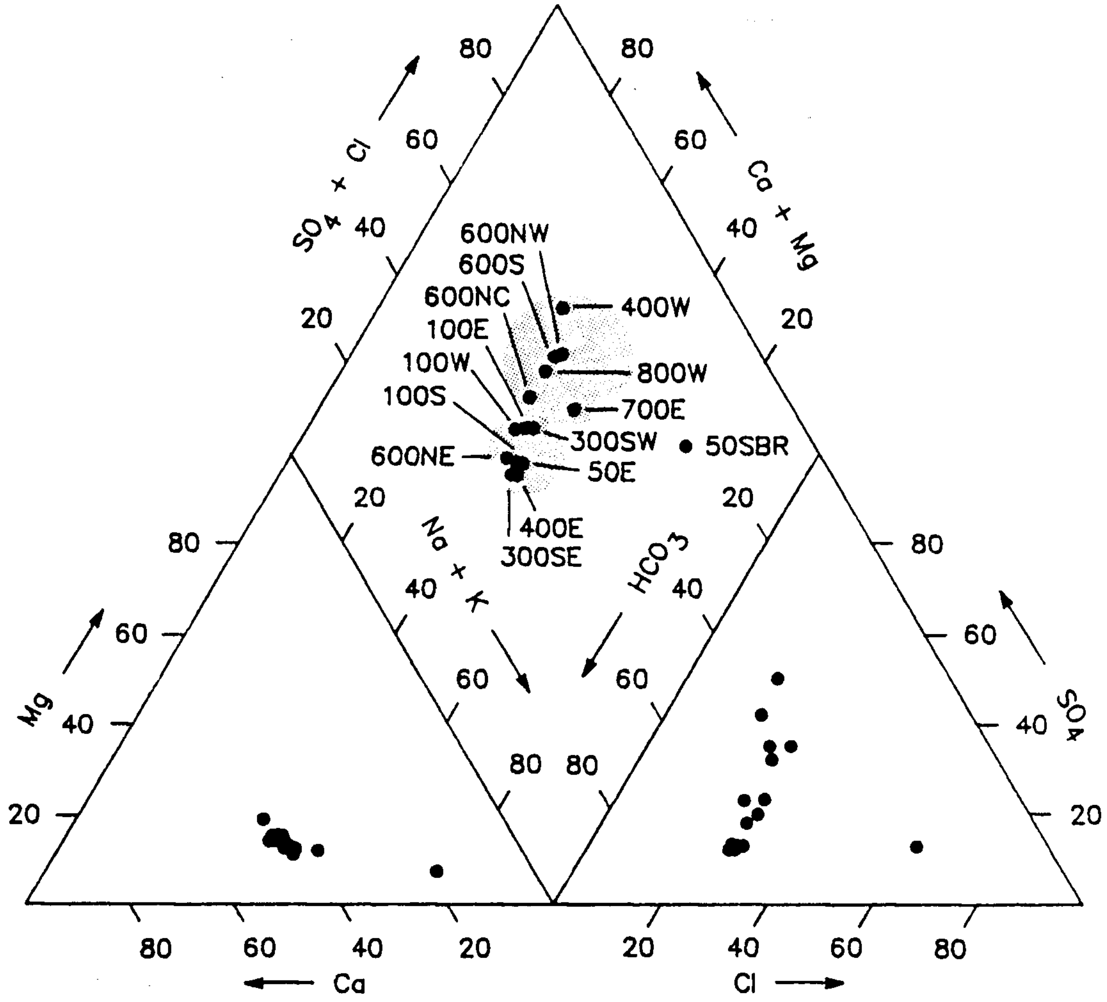

Figure 29. Trilinear diagram showing classification of ground waters based on percent of chemical constituents

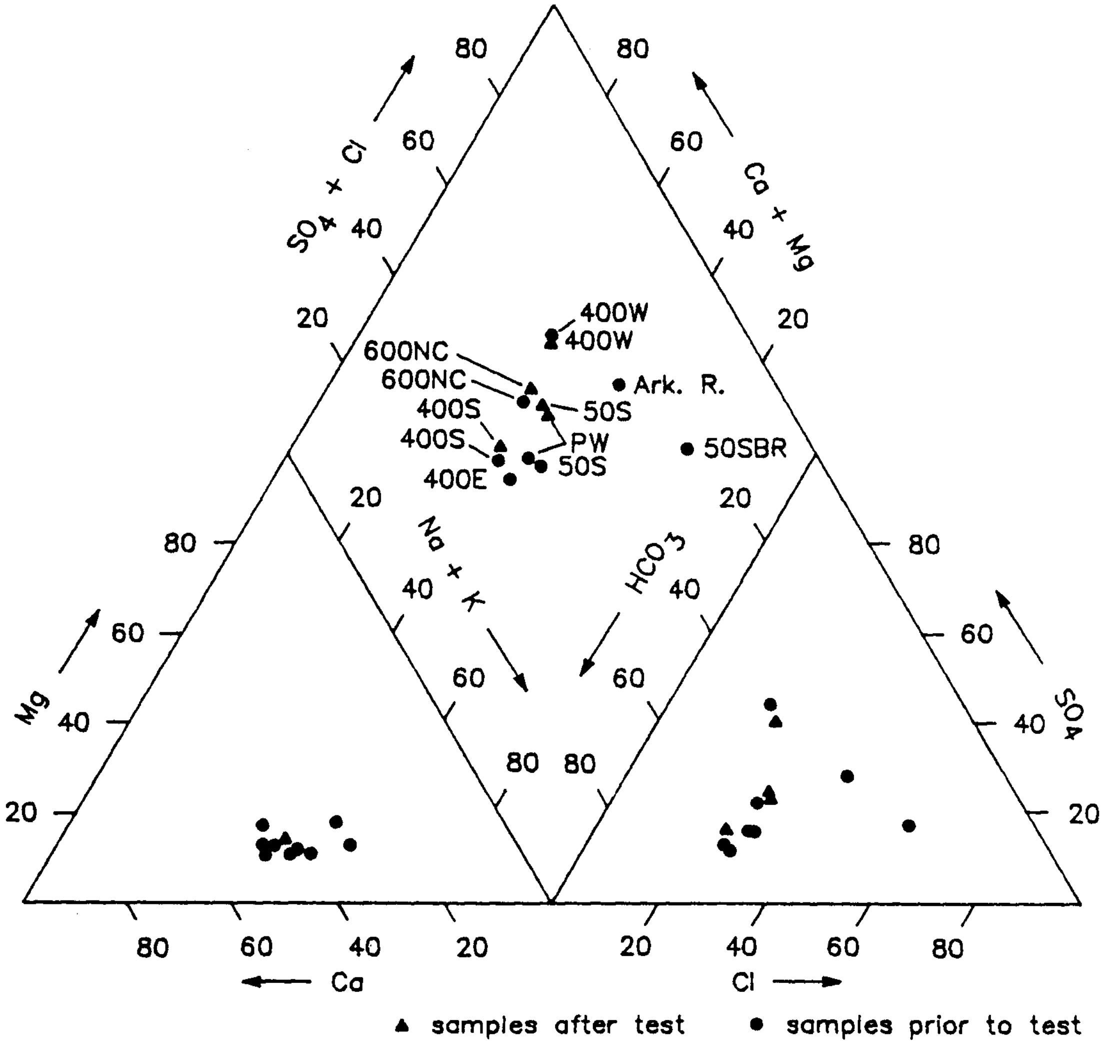

Figure 30. Trilinear diagram showing classification of water chemistry prior to and after the test

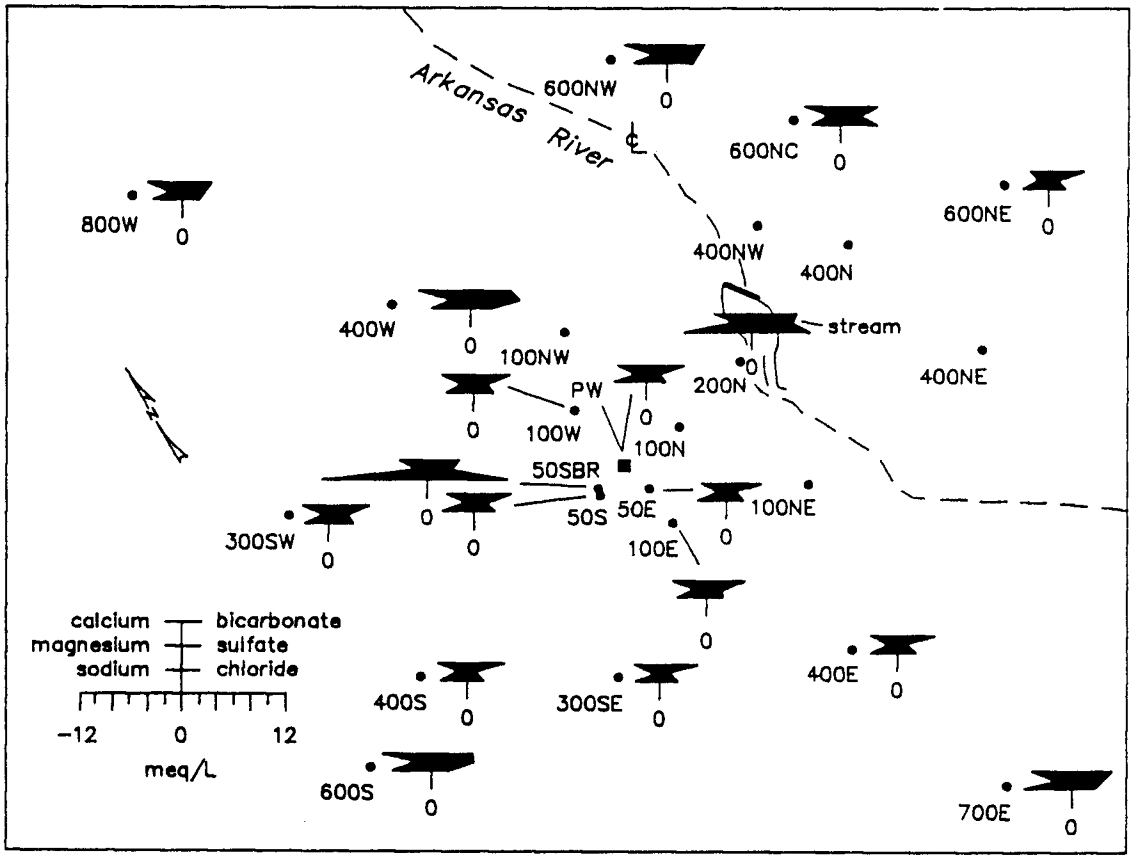

Figure 31. Location map showing variations in water chemistry throughout the test site

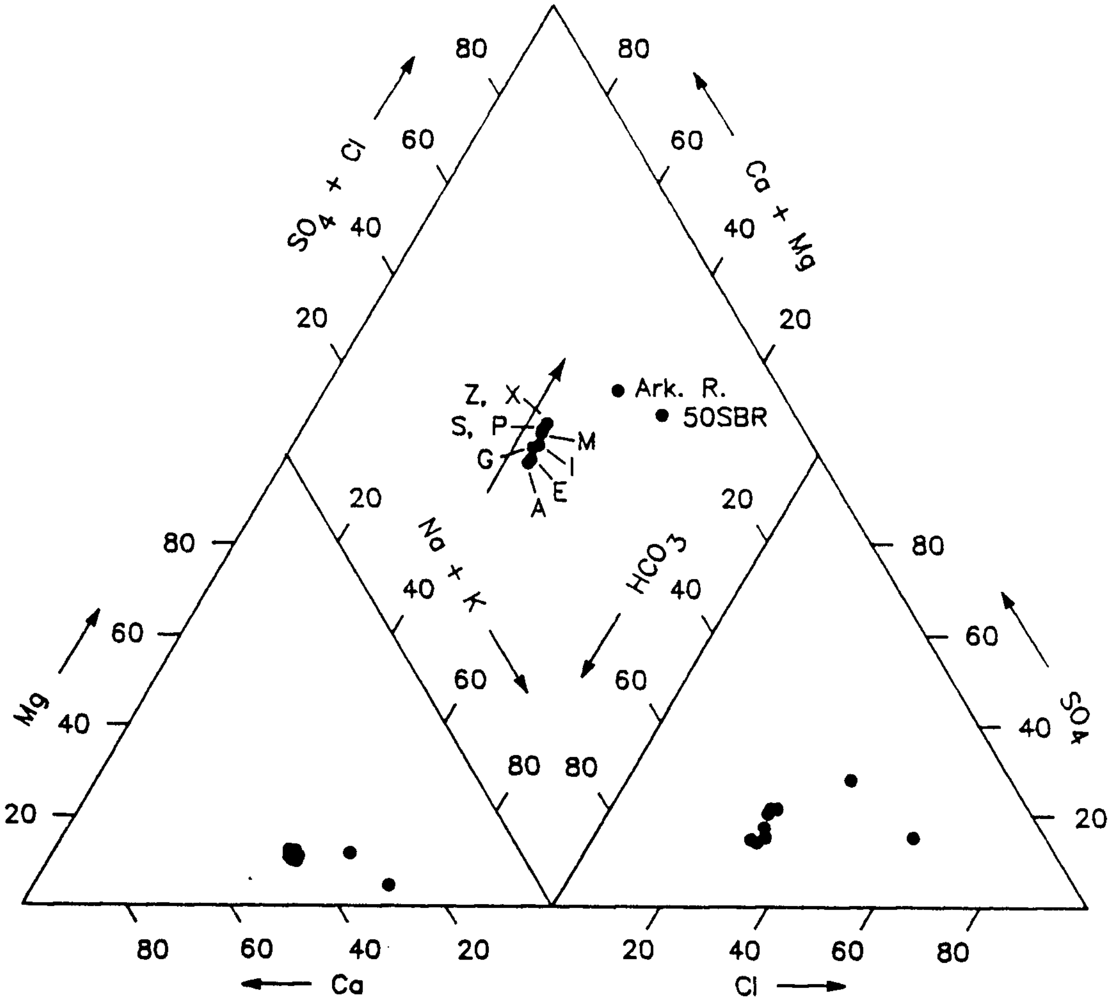

Figure 32. Trilinear diagram showing changes in ground-water chemistry of pumping well during the test

indicate significant quantities of bedrock water mixing with the alluvial water. On the other hand, the Arkansas River has more than sufficient sulfate, chloride, and nitrate to account for the resultant increase of these constituents in the pumping well. By the end of the test, there was an approximate 25 percent increase in calcium (from 67 to 85 mg/L), magnesium (from 12 to 15 mg/L), and a 178 percent increase in nitrate (from 1.8 to 5.0 mg/L) in the pumping well, indicating an Arkansas River water source. The constituents did not change noticeably.

Water chemistry in the pumping well, during the eight-day pumping test, showed a definite increase inconductivity, sulfate, calcium, magnesium, chloride, and sodium values. Statistical analysis by linear regression of the water chemistry from the pumping well versus time (in hours) was used to indicate if the observed trend of increasing concentration with time was statistically significant at the $\underline{a}$ = 0.10 confidence interval. This interval was selected due to the small data set. It was assumed that an acceptable error would be one out of every 10 samples (0.10).

The correlation coefficient is an estimate of the degree of linear interrelationship between variables. As can be seen in Table 7, the observed trend is significant for all of the constituents tested as shown by the correlation coefficient being near 1.00.

TABLE 7. SUMMARY OF STATISTICS FROM LINEAR-REGRESSION ANALYSIS OF THE WATER CHEMISTRY FROM THE PUMPING WELL VERSUS TIME

Element	Correlation Coefficient	Sample Size
Ca	.97	9
Mg	.94	9
Na	.98	9
NO3	.97	9
Cl	.99	20
SO4	.96	20
Conductivity	.96	37

In the 600N group of wells, conductivity increased the closer the well was to the river. The chemistry of 600NE and 600NC wells differed from the chemistry of the 600NW well. After the end of the test, the 600NE had a specific conductivity of 708 μmhos/cm, 600NC had 868 μmhos/cm, and 600NW had 1069 μmhos/cm. These values may indicate an influx of fresher water from the northeast, such as from the direction of Walnut Creek (Figures 1, 5 and 25).

In addition to the inferred ground-water-flow paths, Figure 5 shows the measured ground-water electrical conductivities after the completion of the stream-aquifer test. The area around the pumping well is characterized by fresher ground water and higher water-table elevations than the rest of the area west and southwest of the Arkansas River. The occurrence of higher conductivity water away from the pumping well helps support the idea of a perched water table in the vicinity of the pumping well. A perched water table would prevent or slow down recharge due to rainfall and runoff from reaching the lower aquifer.

The presence of higher conductivity water at the 400W well suggests that a zone of stagnant water may be present. The 400W well is situated in an area where several flow systems may be bypassing each other, thus causing a stagnant point in the flow system with a resulting poorer water quality (Figure 5).

The occurrence of high conductivity water away from the river is observed at the 600N group of wells, 400W, 800W, 600S, and 700E. A possible theory for the presence of increased conductivity water might be the occurrence of an ox-bow pointbar sequence at the outer edge of the test site. Analysis of aerial photos of the site indicate the presence of numerous ox-bows in other parts of the immediate area. There is an abandoned channel that parallels the river in an approximate east-west direction, and there is an overflow channel next to the river between the 100N wells and the 200N well (Figure 4), which indicates that the river is still laterally migrating. The increased conductivity zones may indicate a more permeable zone through which surface water from the Arkansas River is flowing in a circular direction from southwest to southeast. The pump-test data show higher transmissivities for the 400W, 800W and 700E wells (Table 4). The rapid response of the 600S and 800W wells to the pumping of the west irrigation well (W-IRR) suggests that a more permeable zone is present in the vicinity of these wells. The fresher water around the pumping well may reflect perching due to finer sediments deposited as floodplain deposits after the river moved towards the northeast.

Inspection of the water data collected from the observation wells in July 1986, indicated a wide variation in conductivities throughout the site. In particular, the 600S, 800W, 400W, 700E, 600NW and 600NC wells showed conductivities near 900 μmhos/cm and greater. The occurrence of high transmissivities at most of these same wells also suggested the occurrence of more permeable zones throughout the area. Therefore, the data were divided into two groups based on chemistry and transmissivity data. Discriminant-function analysis was used to determine if the observation of the existence of two groups in the data was statistically significant. This method requires defining the two groups a priority. The groups were selected on the basis of specific conductivity, chloride and sulfate concentrations, and transmissivity values. In addition, evaluation of the data plotted on a Piper diagram suggested two distinct groups (Table 8; Figures 30, 31).

A simple linear discriminant function transforms a set of measurements on a sample into a single score. This score represents the sample's position along a line defined by the linear discriminant function. Discriminant analysis consists of finding the maximum separation between groups of data while simultaneously resulting in minimum spread within each group (Davis, 1986).

The discriminant index, R0, is the point along the discriminant function line that is halfway between the center of group I and the center of group II. The center of group I is R1 and the center of group II is R2. Figure 33 shows a plot of the

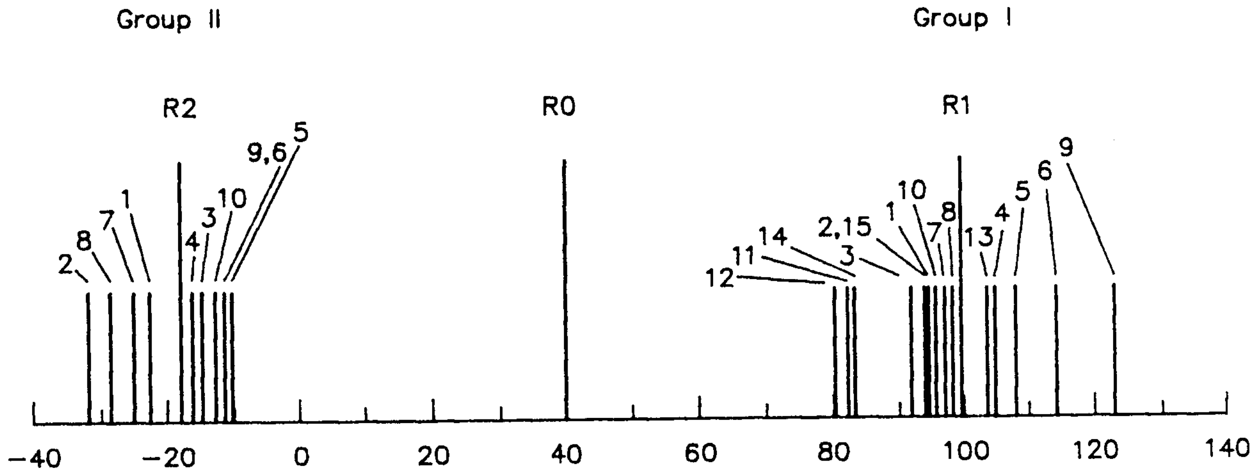

Figure 33. Plot of discriminant analysis groups

data with R0, R1 and R2 midpoints. The data show up as two distinct groups. The values calculated by the test are presented in Table 8.

To evaluate the significance of the discriminant function it is necessary to measure the separation of the two groups. The distance between the midpoints [Mahalanobis' distance (D^2)] is equivalent to the absolute value of subtracting R1 from R2. The value for this test is 116.86 (Table 8). The significance of the distance between midpoints is tested using a form of the F-test (Davis, 1986, p.487). The null hypothesis is that the distance between the two midpoints is zero versus the alternate hypothesis that the distance between the two midpoints is greater than zero. The calculated F-test result is 60.97 with 8 and 16 degrees of freedom. The critical F value at - = 0.10 with 8 and 16 degrees of freedom is 2.45 (Steele and Torrie, 1980) so the alternate hypothesis of the distance between the midpoints being greater than zero is accepted, and the data are shown to be two separate groups.

The use of this test helps to support other data from the test site which suggest that the higher conductivity wells may be in more permeable zones and that extensive pumping may result in mixing of surface water from the Arkansas River with background quality ground water in these areas.

Another line of evidence indicating stream/aquifer interaction at the site is seen by looking at the effects of stream discharge on conductivity values of both stream and

TABLE 8. DISCRIMINANT FUNCTION ANALYSIS OF OBSERVATION-WELL DATA

Na	Ca (mg/l)	Mg	SO_4	Cl	Spec. Cond. (μmhos/cm)	Transmissivity (gpd/ft)	Sample Site
Group I							
86.0	64.0	11.0	60.0	83.0	790.	163788.	50S
75.0	64.0	11.0	44.0	73.0	715.	79237.	50E
71.0	64.0	10.0	42.0	67.0	700.	179310.	400E
69.0	69.0	11.0	55.0	63.0	710.	179310.	400E
76.0	65.0	10.0	45.0	72.0	715.	179310.	400E
66.0	66.0	11.0	42.0	64.0	690.	100318.	400S
66.0	72.0	11.0	57.0	65.0	715.	100318.	400S
76.0	87.0	16.0	118.0	68.0	849.	100318.	400S
83.0	67.0	12.0	62.0	80.0	781.	145150.	PW
70.0	62.0	10.0	40.0	66.0	690.	154125.	300SE
77.0	73.0	12.0	75.0	80.0	795.	155055.	300SW
71.0	73.0	13.0	68.0	73.0	760.	132586.	100W
73.0	66.0	11.0	45.0	70.0	711.	119495.	100S
79.0	74.0	15.0	90.0	68.0	805.	132448.	100E
103.0	111.0	22.0	234.0	73.0	1100.	137897.	600S
Group II							
67.0	64.0	13.0	45.0	69.0	708.	378560.	600NE
102.0	100.0	20.0	185.0	104.0	1069.	393406.	600NW
124.0	87.0	17.0	192.0	95.0	1102.	520393.	700E
73.0	78.0	16.0	132.0	76.0	888.	212236.	800W
103.0	118.0	27.0	267.0	87.0	1205.	207965.	400W
99.0	109.0	25.0	231.0	91.0	1130.	207965.	400W
124.0	145.0	36.0	371.0	95.0	1420.	207965.	400W
74.0	82.0	14.0	91.0	86.0	848.	401274.	600NC
78.0	87.0	15.0	101.0	86.0	860.	401274.	600NC
79.0	86.0	15.0	97.0	88.0	868.	401274.	600NC

Discriminant scores for Group I		Discriminant scores for Group II	
1	94.9879	1	-22.8034
2	93.9076	2	-32.2290
3	91.8522	3	-14.4869
4	104.8008	4	-16.1874
5	107.9118	5	-10.3389
6	114.1092	6	-10.9236
7	97.0613	7	-24.9906
8	98.0723	8	-28.6045
9	123.1776	9	-10.8090
10	96.2488	10	-12.4519
11	82.5097		
12	80.8775		
13	113.5845		
14	83.6817		
15	94.3876		

F = 60.9707 with 8 and 16 Degrees of freedom
Mahalanobis D^2 = 116.86
R1 = 98.4779 R0 = 40.0480 R2 = -18.3821

aquifer. Conductivity data from the Arkansas River shows an inverse trend with the amount of discharge in the stream (Figure 34): as flow decreases, specific conductivity increases; as discharge increases, specific conductivity decreases. Similar trends are observable in the sulfate and chloride data from the stream (Figure 34). There also appears to be a correlation between decreased conductivity values in the pumping well and the storm event that showed up at the 142-hour discharge measurement (Figure 35). The storm event shows up as a decrease in the conductivity of the pumping well at 164.4 hours into the test (Figure 35).

Summary of water-chemistry analysis

(1) Stream-water induced infiltration is affecting the water quality of the aquifer, i.e. stream-aquifer interaction has occurred.

(2) Chemical evidence supports the idea of a perched water zone suggested by the geologic and hydraulic analysis of data.

(3) There is a possible recharge source from the northeast (on the other side of the river) affecting the water quality of the 600N group of wells, especially the 600NE well, and confirming hydraulic indicators to that effect.

(4) The existence of high transmissivities on both sides of the river (600N group site and 400W, 800W and 700E group) indicates the possible meandering or lateral migration shifts of the Arkansas River which also affects the water quality.

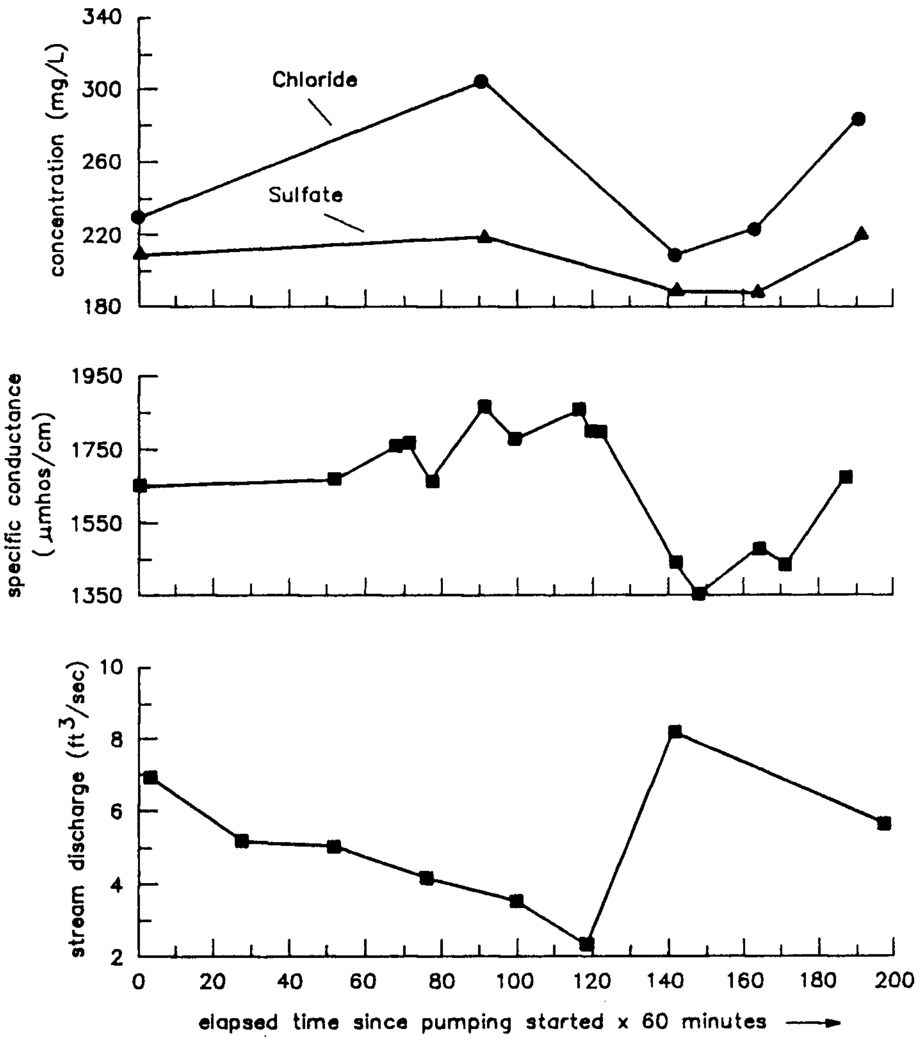

Figure 34. Relationship between stream chemical constituents (chloride, sulfate and specific conductance) and discharge measurements at the central gaging station

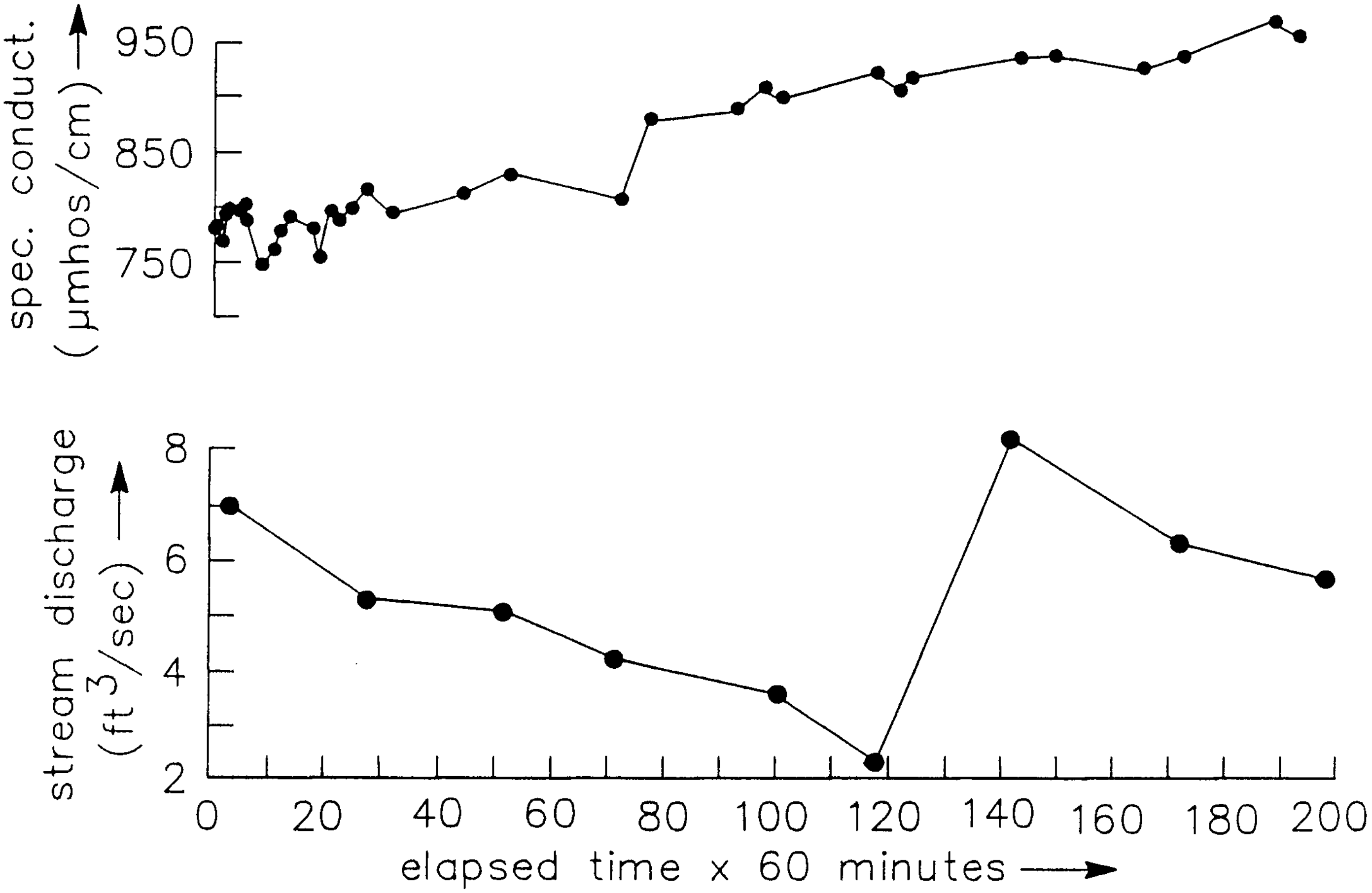

Figure 35. Relationship between specific conductance of ground water from pumping well and stream discharge at the central gaging station

ADDITIONAL WORK ELEMENTS

Additional work elements during this study included two water-level surveys along the Kinsley to Great Bend reach during December 1985 and December 1986 and construction of a series of maps along the Kinsley to Great Bend reach including a base map, a soils map, a bedrock map, two water-level maps, a water-level-change map since December 1985 and a T and S map based on drillers logs. Other work elements included compilation of water rights along the Kinsley to Great Bend reach, the establishment of 9 stream-gaging sites along the Arkansas River and major tributaries, and a seismic-reflection study of the test site (Birkelo et al., 1987).

CONCLUSIONS, LESSONS AND RECOMMENDATIONS

The results of this test indicate that the Arkansas River alluvial aquifer is a prolific aquifer with very high transmissivity. As a result, it readily responds to imposed stresses such as the well pumping. The pumping stress (1750 gpm) during this test affected an area with a radius greater than a mile, demonstrating that irrigation pumping in that aquifer has a significant area of influence and impact on both ground-water levels and streamflows in nearby streams. Drawdown and recharge-boundary effects were observed in all observation wells completed within the aquifer, including the ones on the opposite side of the Arkansas River. The alluvial aquifer did not exhibit a water-table behavior, and "delayed" drainage response was not observed due to a semiconfining clay layer less than 10 feet and an additional recharge source from the nearby Walnut Creek-alluvial system. Actual streamflow depletion due to ground-water pumping was appreciably less than the computed depletion based on analytical solutions.

Pumping tests are the most reliable way of obtaining aquifer properties for use in developing ground-water supplies, in predicting numerical simulations and in management of water resources. However, they are expensive tests because of both the required equipment and manpower.

This stream-aquifer study has provided valuable experience to KGS staff and students, as well as to staff members of various cooperating agencies (see acknowledgments). It also proved to be a valuable and educational experience for students from the University of Kansas and Fort Hays University who visited the site during the testing period.

As a result of this study, several lessons were learned or reinforced. Adequate time should be allowed in conducting such studies so as to cover any delays in the field. The logging vehicle is an indispensable drilling accessory, and despite the fact that it may seem inefficient timewise, the logging vehicle should be present during drilling and sampling, so as to immediately deduce the geology of the area and redirect drilling. Had this been the case, several shallow wells completed on top of the semiconfining layer and immediately below it would have been installed.

In testing alluvial aquifers, a minimum of several weeks pumping should be carried out to allow the aquifer to fully respond and adjust to the imposed stress, if meaningful results on storativities, transmissivities, leakances and boundary effects are expected. In our case, the aquifer storativity could not be determined using the neutron probe because the time scale of the test was not long enough to allow dewatering of the upper aquifer unit through the underlying clay layer. Had the drawdown extended below the clay layer, which could possibly happen through a longer duration pumping stress, the derived aquifer storativity might have been different.

Also, in conducting stream-aquifer tests, the first seconds and few minutes are essential to data analysis and interpretation. Data interpretation would have been much easier in this case if we had measurements during the first seconds after pumping started so that a better curve matching could be obtained.

A better system needs to be developed for maintaining constant and stable pumping rate than the one employed in this test, which involved a hard-to- manipulate throttle without any fine-tuning capability.

To complete this test, a three-dimensional numerical simulation of the stream-aquifer system at the pumping-test site may be required. Through this type of simulation, all fundamental questions posed and answered in this report could be validated and reinforced.

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