Vertical-Deformation, Water-Level, Microgravity, Geodetic, Water-Chemistry, and Flow-Rate Data Collected During Injection, Storage, and Recovery Tests at Lancaster, Antelope Valley, California, September 1995 through September 1998

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	929.0	square centimeter
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer
	Volume	
acre-foot (acre-ft)	1,233	cubic meter
acre-foot (acre-ft)	0.001233	cubic hectometer
cubic foot (ft^3)	0.02832	cubic meter
	Flow Rate	
gallon per minute (gal/min)	0.06309	liter per second
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram
	Pressure	
pound per square inch (lb/in^2)	6.895	kilopascal

Temperature in degrees Celsius (^oC) can be converted to degrees Fahrenheit (^oF) by the following equation:

$$^oF = (1.8\ ^oC) + 32.$$

Changes in land-surface altitudes from differential-leveling surveys were measured in metric units and shown in this report as metric units so that comparisons can be made with GPS data shown in this report. Coordinates determined by Global Positioning System (GPS) surveying generally are reported in metric units. The industry standard for GPS usage is that field measurements are done in the metric system.

Vertical Datum

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated Water-Chemistry Units

Chemical concentration is given either in milligrams per liter (mg/L) or micrograms per liter (µg/L). Micrograms per liter is equivalent to "parts per billion." Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at ^{o}C).

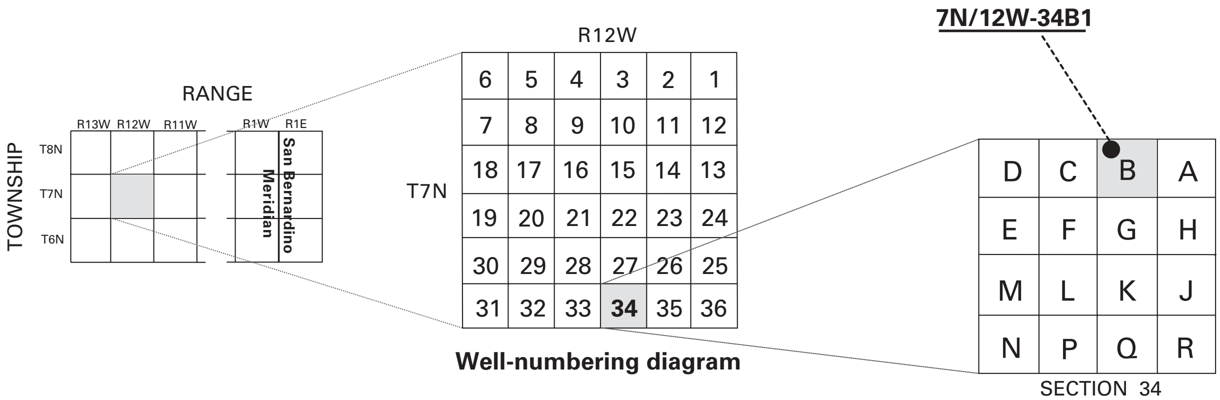
Abbreviations and Acronyms

cm	centimeter
mGal	milliGal
µGal	microGal
µm	micrometer
V	volt

AC	alternate current
AHr	ampere-hour
AVEK	Antelope Valley–East Kern Water Agency
Caltrans	California Department of Transportation
CSBM	Los Angeles County Surveyor Bench Mark
GPS	Global Positioning System
LAC	Los Angeles County Department of Agricultural Commissioner and Weights and Measures
LACDPW	Los Angeles County Department of Public Works
LINJ	Lancaster INJection well
NAD27	North American Datum of 1927
NAD83	North American Datum of 1983
NEIC	National Earthquake Information Center
NGVD29	National Geodetic Vertical Datum of 1929
NTU	nephelometric turbidity unit
NWIS	National Water Information System
PVC	polyvinyl chloride
SCEC	Southern California Earthquake Center
SCIGN	Southern California Integrated GPS Network
SWP	State Water Project
THM	trihalomethane
TON	threshold odor number
USGS	U.S. Geological Survey

Well-Numbering System

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with “A” in the northeast corner of the section and progressing in a sinusoidal manner to “R” in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humbolt (H), Mount Diablo (M), and San Bernardino (S). All wells in the study area are referred to the San Bernardino base line and meridian (S). Well numbers consist of 15 characters and follow the format 007N012W34B001S. In this report, well numbers are abbreviated and written 7N/12W-34B1. The following diagram shows how the number for well 7N/12W-34B1 is derived.



Well-numbering diagram

Vertical-Deformation, Water-Level, Microgravity, Geodetic, Water-Chemistry, and Flow-Rate Data Collected During Injection, Storage, and Recovery Tests at Lancaster, Antelope Valley, California, September 1995 through September 1998

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ABSTRACT

A series of freshwater injection, storage, and recovery tests were conducted from September 1995 through September 1998 to evaluate the feasibility of artificially recharging ground water in the Lancaster area of the Antelope Valley, California. The tests used two production wells at a well field located in the southern part of the city of Lancaster. Monitoring networks were established at or in the vicinity of the test site to measure vertical deformation of the aquifer system, water-level fluctuations, land-surface deformation, water chemistry, and injection well flow rates during water injection and recovery. Data presented in this report were collected from a dual extensometer; 10 piezometers; 1 barometer; 27 active or abandoned production wells; 31 gravity stations; 124 bench marks; 1 permanent and 1 temporary continuous Global Positioning System (GPS) station; 3 tiltmeters; and 2 electromagnetic flowmeters from September 1995 through September 1998. This report discusses the location and design of the monitoring networks and the methods used to collect and process the data, and presents the data in tables and graphs.

INTRODUCTION

Historically, ground-water withdrawals in the Lancaster area of the Antelope Valley in southern California have exceeded natural replenishment, resulting in overdraft and land subsidence. Since the 1920’s, ground-water levels have declined as much as 200 feet (ft) in the area and land subsidence has exceeded 6 ft in some areas (Ikehara and Phillips, 1994). Reliance on ground water eased somewhat in the 1970’s due to the importation of surface water from northern California by way of the State Water Project (SWP) and the California Aqueduct. However, rapid population growth and the resulting demand for water has increased ground-water withdrawals and renewed concerns about overdraft and subsidence.

To address these concerns, the U.S. Geological Survey (USGS), in cooperation with the Los Angeles County Department of Public Works (LACDPW) and the Antelope Valley–East Kern Water Agency (AVEK), conducted a series of freshwater injection, storage, and recovery tests in the Lancaster area of the Antelope Valley, California, from September 1995 through September 1998 as part of a study to evaluate the feasibility of artificially recharging the ground-water system in the Lancaster area. The objectives of the study were to (1) develop a better understanding of the aquifer system, (2) assess the effects of injection, storage, and recovery on the aquifer system, and (3) develop tools to help plan and manage a larger injection program.

The USGS role in this study was to collect and analyze hydraulic and aquifer-system deformation data, develop a simulation/optimization model for use in designing and managing a larger-scale injection program, and determine the factors controlling the formation and fate of trihalomethanes (disinfection by-products) in the aquifer system. This report describes the methods of data collection and presents the data collected during the injection, storage, and recovery tests from September 1995 through September 1998. Subsequent reports will describe the use of microgravity surveys to determine water-level changes (Jim Howle, U.S. Geological Survey, written commun., 2000), the determination of the formation and fate of trihalomethanes (Miranda Fram, U.S. Geological Survey, written commun., 2000; Roger Fujii, U.S. Geological Survey, written commun., 2000); and the development of a simulation/optimization model (Steve Phillips, U.S. Geological Survey, written commun., 2000).

As part of the injection, storage, and recovery tests, monitoring networks were established to measure vertical deformation of the aquifer system, ground-water levels, changes in microgravity, land-surface deformation, injection and extraction water chemistry, and injection and extraction flow rates. Compaction and expansion were measured at a dual extensometer site; barometric pressure was also measured at the site. Water levels were monitored at 13 active and abandoned production wells and 10 nested piezometers. Microgravity was measured at 31 stations. Geodetic data was collected at 124 vertical-control bench marks, 1 permanent and 1 temporary continuous Global Positioning System (GPS) stations, and 3 tiltmeters. Water-chemistry samples were collected from 17 active production wells and the 10 nested piezometers and analyzed. Flow data were collected using meters mounted on two wells used for water injection.

Description of Study Area

The study area encompassed several square miles within and just south of the city of Lancaster, Antelope Valley, California (fig. 1). Lancaster is in the south central part of the valley, in the western part of the Mojave Desert, and is about 50 miles (mi) north of Los Angeles. The Antelope Valley is a triangular-shaped, topographically closed basin covering about 2,200 square miles (mi^2). Annual rainfall at Lancaster averaged about 8.0 inches for 1974–98 (Western Regional Climate Center, accessed July 10, 1999). Amargosa Creek, the most prominent natural surface feature in the study area, trends north and northwest through the study area. Amargosa Creek is ephemeral, and flow generally occurs only after periods of intense rainfall. Land use is a mixture of light industrial, commercial, and residential development interspersed with large tracts of undeveloped land.

Bloyd (1967) divided the valley into 12 ground-water subbasins based on locations of faults, bedrock, and physiographic boundaries. The study area is in the Lancaster subbasin (fig. 1), which is filled with alluvial and lacustrine deposits, which, in places are as much as 5,000 ft thick (Brenda and others, 1960; Mabey, 1960; Londquist and others, 1993). The alluvial deposits consist of interbedded heterogeneous mixtures of fine-grained silt, coarse-grained sand, and gravel (Dutcher and Worts, 1963; Bloyd, 1967; Durbin, 1978), and the lacustrine deposits primarily consist of thick layers of blue-green silty clay and brown clay; the clay layers are interbedded with sand and silty sand layers (Dibblee, 1967). Stratigraphic, hydrologic, and water-chemistry data were used to divide the water-bearing deposits in the Lancaster subbasin into three aquifers: the upper, middle, and lower (David Leighton, U.S. Geological Survey, written commun., 2000). The upper aquifer extends from the water table to an altitude of about 1,950 ft above sea level, the middle aquifer extends from 1,950 to 1,550 ft above sea level, and the lower aquifer extends from 1,550 ft above sea level to the altitude at which bedrock is encountered (fig. 2). In the study area, ground-water flow in the upper aquifer is unconfined to partly confined at depth. Ground-water flow in the lower aquifer is confined by the lacustrine deposits (Londquist and others, 1993). Sneed and Galloway (2000) reported that most of the compaction in the Lancaster area has been caused by dewatering of the lacustrine deposits and other fine-grained alluvial deposits.

Acknowledgments

Individuals who provided assistance and support for this study include Joe Aja, Dean Efstathiou, Mustafa Arika, Eleni Hailu, Dan Jones, Kenneth Rosander, and Eugene Betts of the Los Angeles County Department of Public Works, and Wallace Spinarski and Russell Fuller of the Antelope Valley–East Kern Water Agency.

Field office personnel of the Los Angeles County Department of Public Works, Waterworks and Sewer and Maintenance Division, Lancaster, constructed a building to house the dual extensometer and shelters for two sets of nested piezometers, and kept the injection cycles running despite the various mechanical challenges that arose throughout the study.

Francis Riley and Devin Galloway of the U.S. Geological Survey designed the dual extensometer, provided guidance during its construction, and assembled the above-ground instrumentation.

Robert Reeder and Darrel Bozarth of the Los Angeles County Department of Public Works, Survey

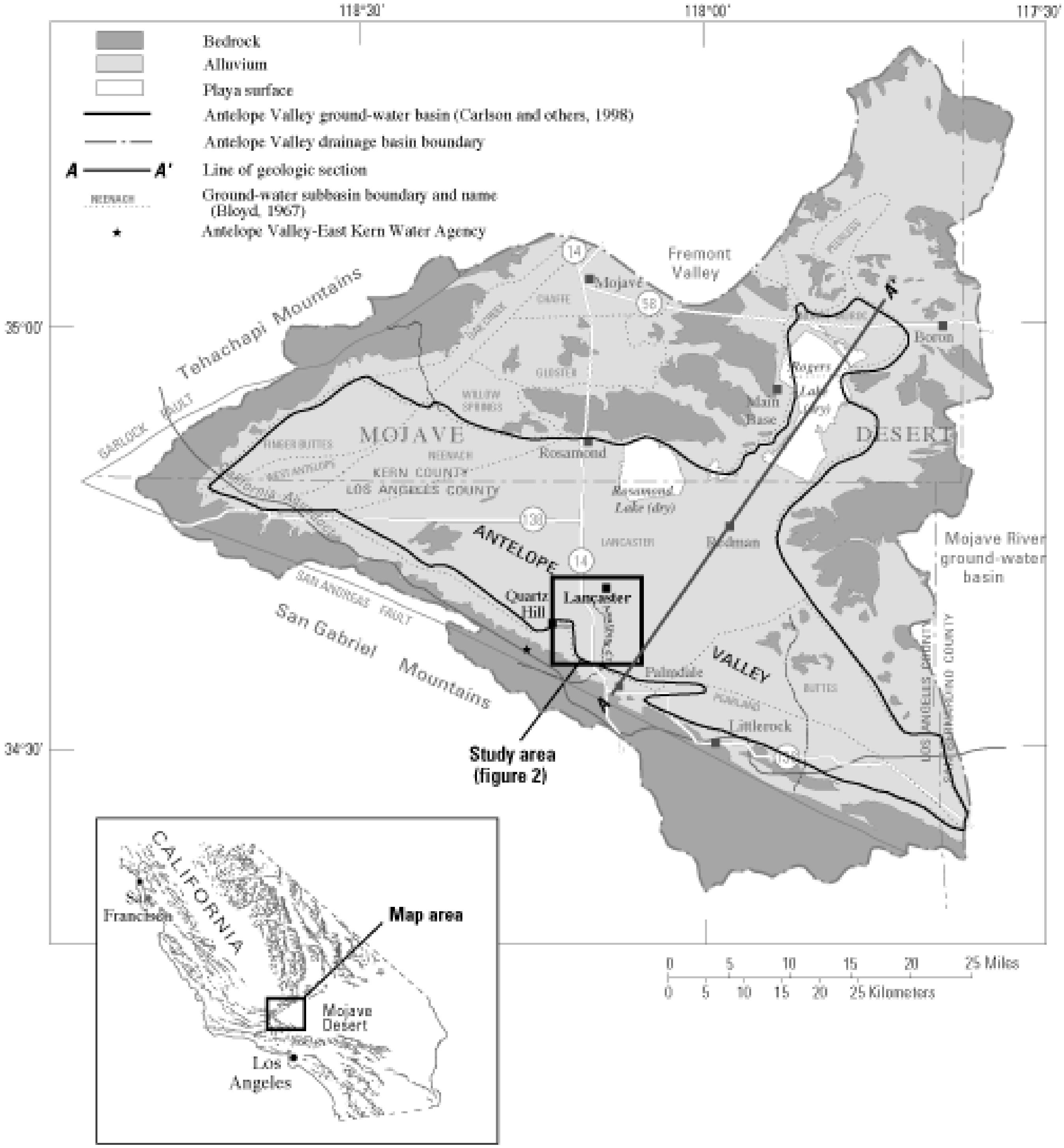


Figure 1. Generalized surficial geology and location of study area and of ground-water basin and subbasins in the Antelope Valley, California. (Modified from Carlson and others, 1998)

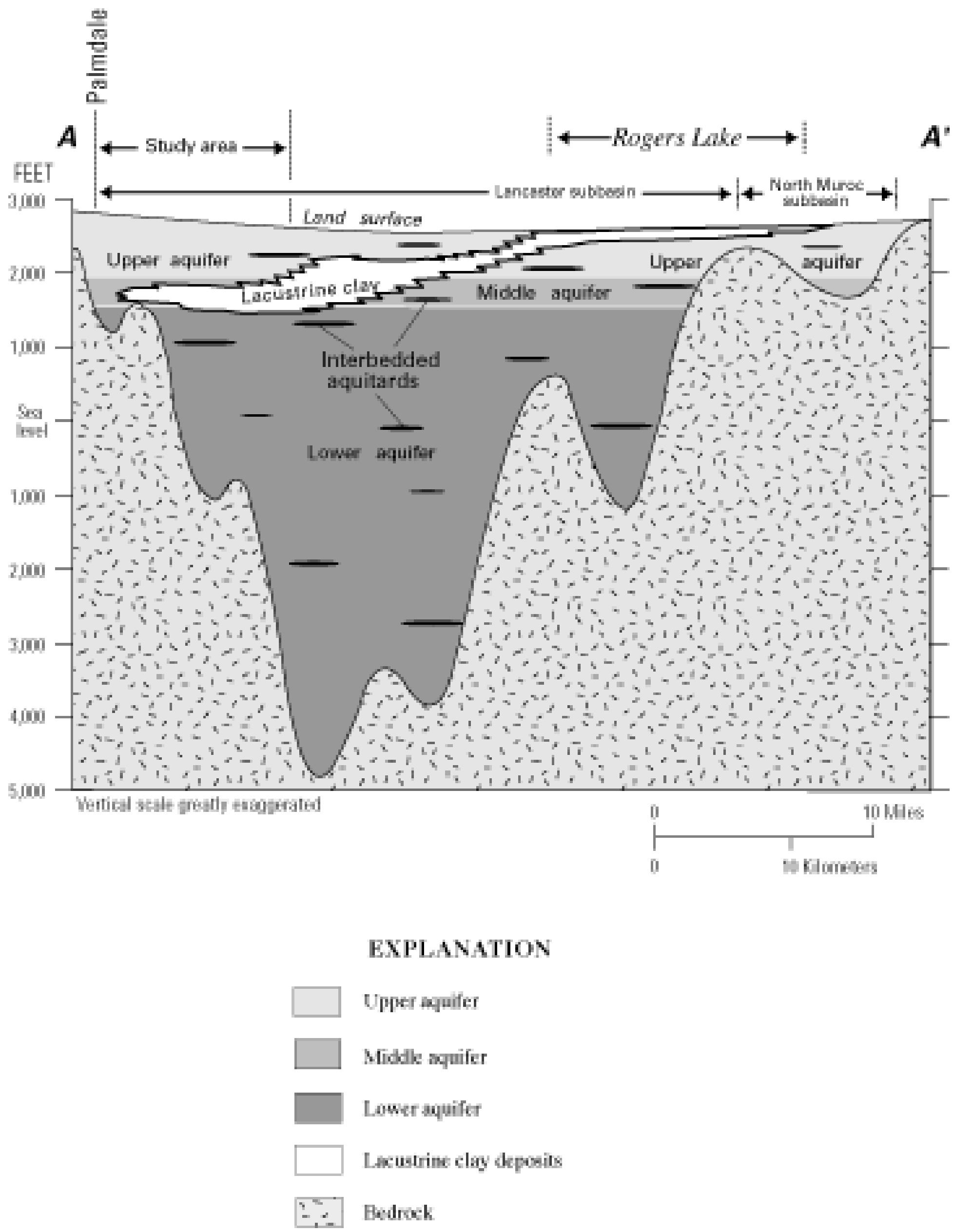


Figure 2. Generalized geologic section showing relation of lacustrine clay deposits to younger and older alluvium and aquifers in the Lancaster and North Muroc subbasins in the Antelope Valley ground-water basin, California (modified from Londquist and others, 1993). Line of section is shown on figure 1.

Division, assisted in locating buried utilities and in organizing equipment, materials, and manpower for construction of the microgravity and differential-leveling networks. Donald Pool, U.S. Geological Survey, shared expertise in designing and implementing the microgravity surveys. Michael Carpenter, U.S. Geological Survey, provided useful insight regarding the performance characteristics of the particular gravity meter used in this study.

Charles Peer, Gerald Campbell, and the surveying crew of the Los Angeles Department of Public Works, Survey Division, assisted with the establishment and repeated surveying of the differential-leveling network.

Kenneth Hudnut, U.S. Geological Survey, contributed the equipment and expertise for installing and operating a permanent continuous GPS station at the injection site. The GPS station was constructed by Daryl Baisley, Southern California Earthquake Center. GPS data was processed and provided by Jeffrey Behr, Southern California Earthquake Center, and Nancy King, U.S. Geological Survey. Additional GPS equipment was provided by Wayne Vallantine of the California Department of Transportation (Caltrans), Division 7.

Robert Larson of the Los Angeles County Department of Public Works, Materials Engineering Division, installed and operated the tiltmeter network.

Water-chemistry data and information on analytical methods were provided by Maureen Smith, Antelope Valley–East Kern Water Agency; Wilhelmina Solinap, Los Angeles County Department of Agricultural Commissioner and Weights and Measures, Environmental Toxicology Laboratory; and Ramy Gindi, Los Angeles County, Department of Public Works, Sewer and Maintenance Division.

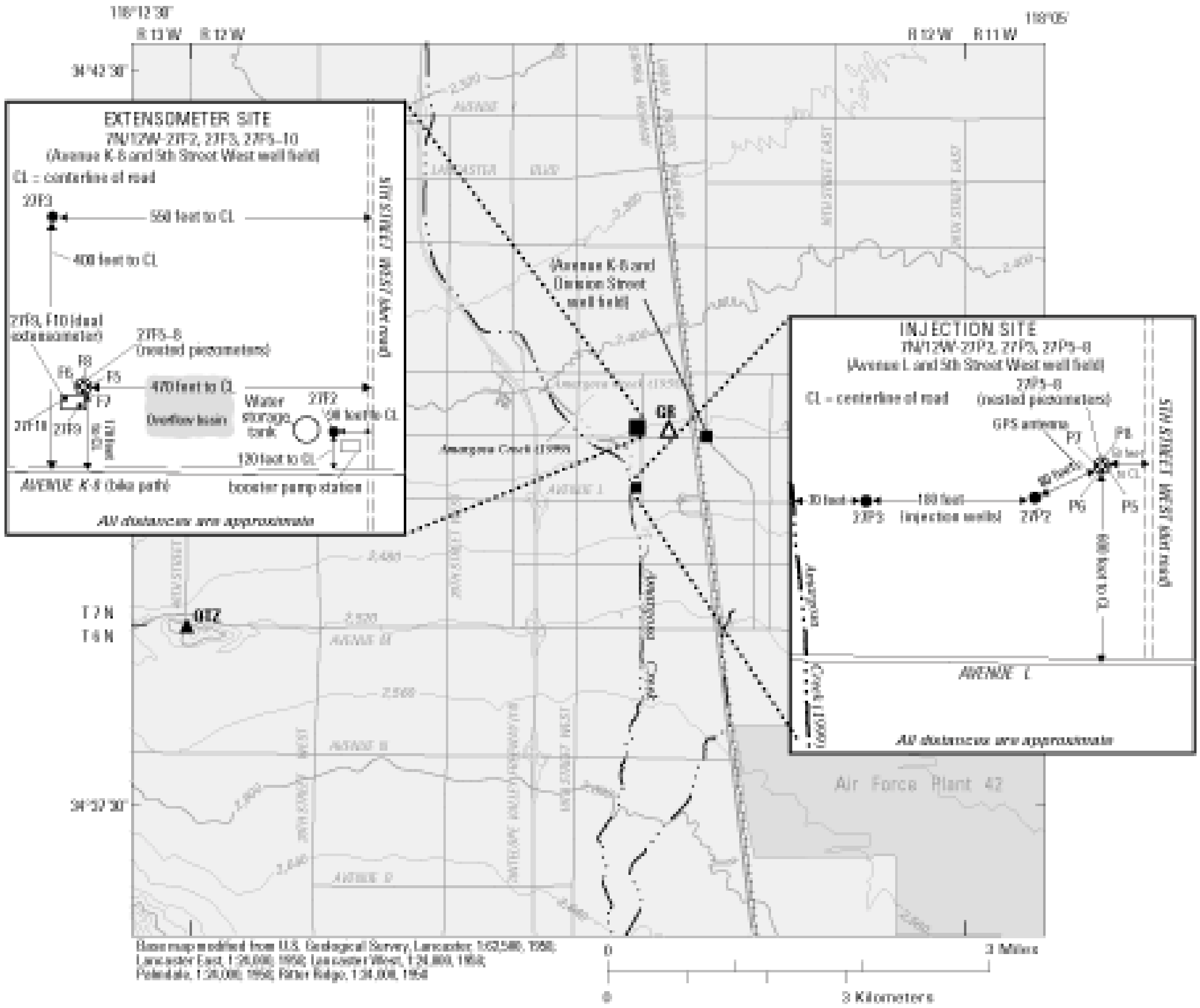
Permission to access privately owned wells to measure water levels was provided by American Auto Sales Incorporated, the U.S. Department of the Air Force and Lockheed-Martin, the El Dorado Mutual Water Company, the West Side Park Mutual Water Company, and the White Fence Farms Water Company.

INJECTION SITE AND TEST DESIGN

Two production wells (7N/12W-27P2 and 27P3) in the LACDPW well field (hereinafter referred to as the injection site) at Avenue L and 5th Street West in Lancaster (fig. 3) were used for direct well injection during the injection, storage, and recovery tests. This site was selected because water from the SWP could be conveyed to the well field through an existing water-distribution system connected to AVEK pipelines. This site also is fairly isolated from engineered structures that could be damaged by changes in land-surface altitude during the tests or that might interfere with data collection. These two wells were selected for injection because each is completed entirely within the upper and middle aquifers. These aquifers have larger transmissivities and storativities than the lower aquifer and therefore are better suited for injection and recovery (Devin Galloway, U.S. Geological Survey, unpublished data, 1995).

Imported surface water from the SWP was used for well injection because it likely will be the source for future injection water, it was available in the quantities required for the tests, and its chemical composition differed from local ground water and thus could be monitored during the tests. SWP water was conveyed to the injection site from the East Branch of the California Aqueduct at AVEK's Quartz Hill Water Treatment Plant through AVEK's south feeder line and a series of secondary LACDPW distribution lines. LACDPW personnel modified the water lines at the injection site by installing valves to reduce line pressure of the injection water from about 80 pounds per square inch (lb/in^2) to less than 30 lb/in^2 and to control the rate of flow to each well. The injected water moved by gravity through the well column, or 4-inch conductor pipe, and into the aquifer through perforations in the well casing.

Three cycles of aquifer injection, storage, and recovery were completed between September 1, 1995, and September 30, 1998 (fig. 4). Each injection phase lasted 1 to 5 months. Water was injected into wells 7N/12W-27P2 and 27P3 during cycle 1 and cycle 2, but only into well 7N/12W-27P2 during cycle 3. A fairly constant injection rate [between 750 and 800 gallons per minute (gal/min)] was maintained during all three cycles. Each injection phase was followed by a 2- to 4-week storage phase that allowed the aquifer system to partially equilibrate. During the storage phase, other LACDPW production wells within 2 mi of the injection site were not operated. After the storage phase, ground water was pumped from the injection wells into LACDPW's water-distribution system, marking the beginning of the recovery (extraction) phase. One or both of the injection wells were continuously pumped for at least 5 months, except for periods of mechanical problems or maintenance work. During the recovery phase, other LACDPW production wells that had been shut down for the injection and storage phases were returned to normal operation. At least 2 weeks prior to the beginning of subsequent cycles, both the injection wells and the surrounding LACDPW production wells were shut down allowing the aquifer system to partially equilibrate.



EXPLANATION

2,640 — **Land-surface altitude**—Contour interval 40 feet. Datum is sea level

▲QTZ Quartz Hill bedrock reference station

△GR Gravity reference station

Figure 3. Locations of the injection site, the extensometer site, and the area of the injection, storage, and recovery study at Lancaster, Antelope Valley, California. Amargosa Creek (1999) reflects changes in the creek owing to channel realignment.

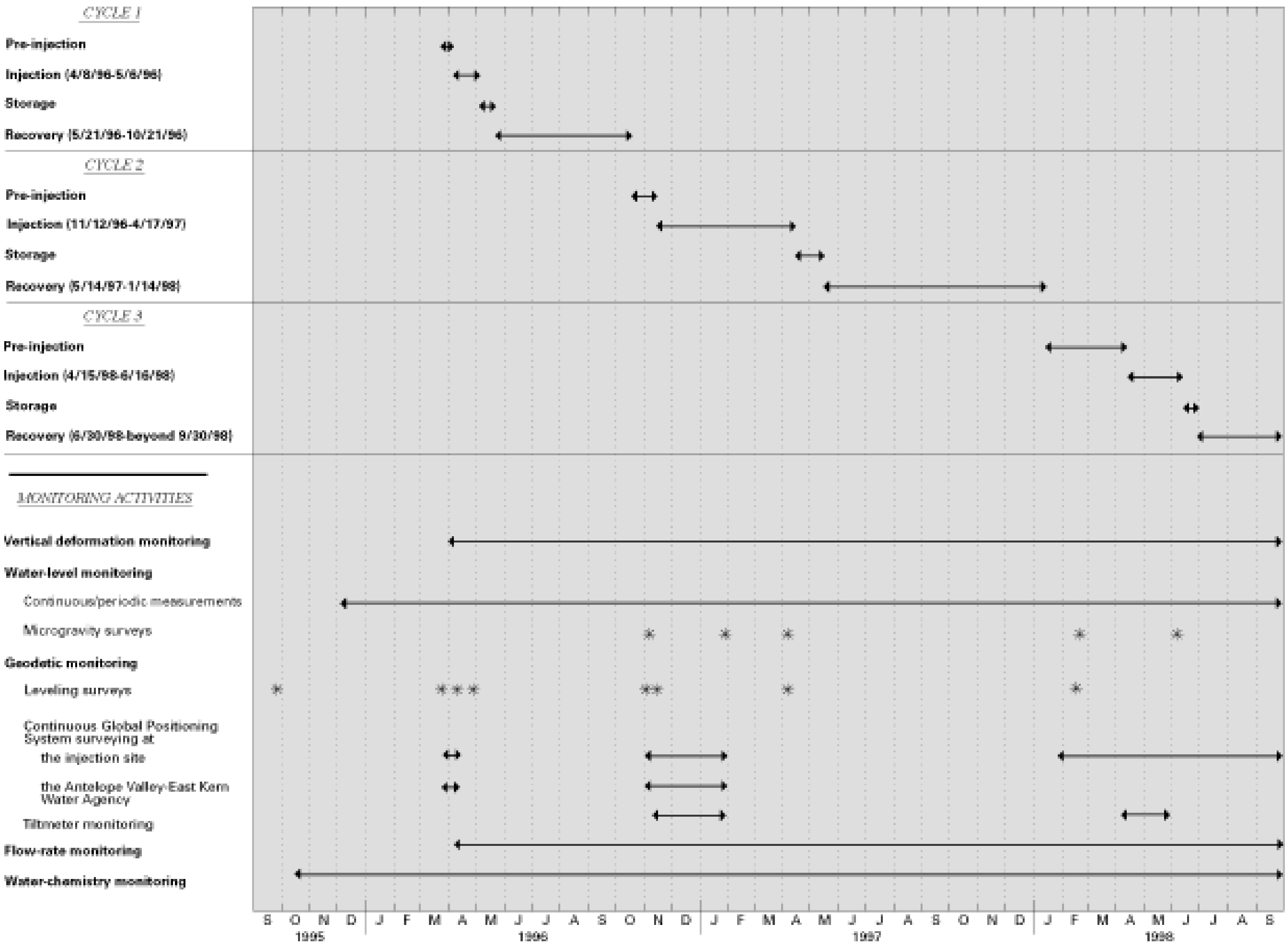


Figure 4. Time line of activities associated with cycles 1–3 of the injection, storage, and recovery study and with monitoring at Lancaster, Antelope Valley, California, September 1995 through September 1998.

VERTICAL DEFORMATION MONITORING

Vertical deformation of the aquifer system (compaction and expansion) was monitored using a dual extensometer (individual shallow and deep extensometers sharing the same instrument table and shelter). An extensometer measures vertical deformation between a specified depth of several feet below land surface and the depth of the extensometer. The dual extensometer was designed to differentiate vertical deformation in the upper and middle aquifers from vertical deformation in the lacustrine unit and lower aquifer. Extensometers generally are not used to measure subsidence; if compressible sediments occur below the depth of the extensometer, measured compaction generally is less than subsidence (Hanson, 1989).

Dual-Extensometer Construction

The dual extensometer was constructed at the LACDPW Avenue K-8 and 5th Street West well field (hereinafter referred to as the extensometer site), about 0.5 mile north of the injection site (fig. 3). The borehole for the shallow extensometer was drilled to 735 ft below land surface, corresponding to the bottom of the middle aquifer and top of the lacustrine unit. The borehole for the deep extensometer was drilled to 1,205 ft below land surface, which is about 300 ft below the lacustrine unit, corresponding to the top of the lower aquifer. Inclinometer measurements made at depth intervals of about 100 ft during drilling indicate that the shallow and deep boreholes deviated from vertical by less than 0.5 and 1.0 degree, respectively. Riley (1986) noted that extensometer boreholes should be vertically aligned to prevent stick-slip friction between the measuring element and the casing. Excessive stick-slip friction can degrade extensometer measurements.

A 6.6-inch outer-diameter steel casing was anchored in cement at the bottom of each borehole (fig. 5). A series of three slip joints was installed along the well casing string. Each slip joint allowed the casing string to change length by as much as 4 ft, and each joint was precompressed by 1 ft to allow vertical displacement in either direction. The slip joints were used to minimize negative skin friction. Negative skin friction occurs between the casing and sediments adjacent to the borehole and can cause the extensometer instruments to under record compaction or expansion by redistributing vertical stresses near the borehole. To further reduce negative skin friction, the annular space between the casing and the borehole was grouted with low-friction bentonite.

A 12-inch diameter surface casing was placed to about 48 ft below land surface in each borehole to prevent infiltration of surface runoff. A 2-inch steel extensometer pipe (the measuring element) was placed inside each casing and rested at the bottom of the borehole. The bottom of the extensometer pipe was about 700 ft below land surface in the shallow extensometer and about 1,180 ft below land surface in the deep extensometer.

A 20- by 15-foot shelter was constructed over the dual extensometer. An instrument table was positioned over both extensometers. The table was mounted on three 4-inch diameter steel legs that were cemented in holes bored to a depth of 16 ft below land surface. To minimize the effect of shallow sediment movement on the extensometer measurements, each table leg was encased in a 6-inch polyvinyl-chloride (PVC) casing, and cardboard forms were placed around the table legs and the 12-inch diameter extensometer surface casings to decouple them from the concrete pad constructed for the shelter foundation. Because the instrument table legs were anchored 16 ft below land surface, the shallow extensometer measured vertical deformation between 16 and 700 ft below land surface, and the deep extensometer measured vertical deformation between 16 and 1,180 ft below land surface.

The extensometer pipe was supported above ground by a fulcrum assembly consisting of a fulcrum arm positioned on an arm support welded to the outside of the 12-inch surface casing and balanced with lead counterweights (fig. 6). Following the guidelines of Riley (1986), the weight of the extensometer pipe was counterbalanced to minimize flexing of the pipe to prevent the pipe from contacting the well casing. The asymmetrical positioning of the fulcrum arm afforded the arm a mechanical advantage of about 8:1 because it reduced the required counterweight from 1,440 to 180 pounds for the shallow extensometer and from 3,360 to 420 pounds for the deep extensometer.

Dual-Extensometer Instrumentation

Vertical deformation (compaction and expansion) of the aquifer system was measured by recording the movement of the instrument table relative to the top of the extensometer pipe using digital and graphical methods. A linear potentiometer (transducer) with a resolution of about 0.0001 was the primary

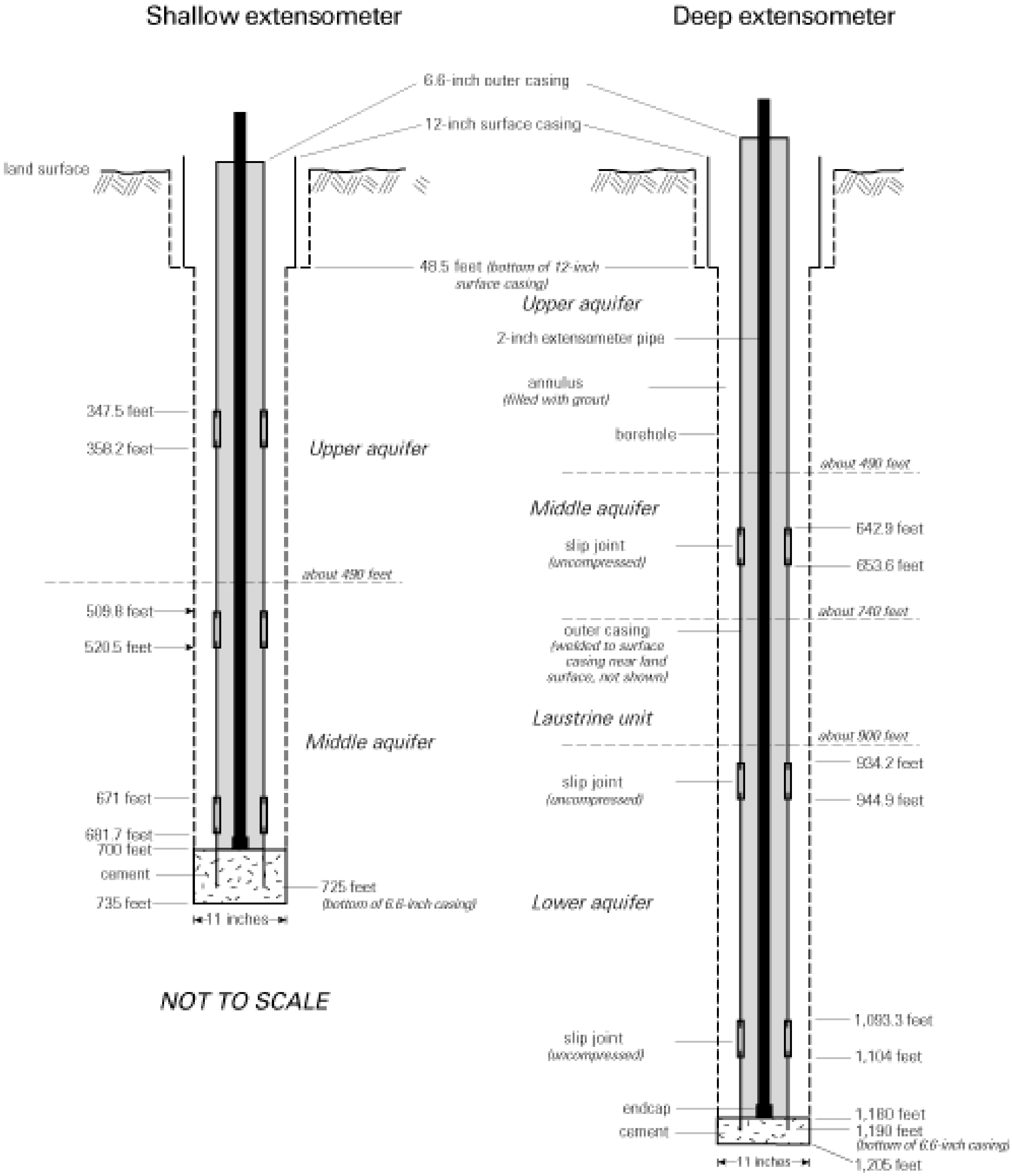


Figure 5. Below-ground installation of the dual extensometer at the Avenue K-8 and 5th Street West well field in Lancaster, Antelope Valley, California.

instrument for each extensometer. The top of the linear potentiometer was secured to the instrument table, and the bottom was secured to the extensometer pipe (fig. 6). As the instrument table moved relative to the extensometer pipe, the linear potentiometer output a voltage proportional to the displacement. The output voltage was recorded on an electronic data logger inside the shelter.

Analog dial gages also were used to measure vertical deformation. The dial gages were attached to pieces of angle aluminum affixed to the instrument table (fig. 6). A spring-controlled stem protruding from the bottom of the dial gage rested on a fixed reference surface attached to the extensometer pipe. The stem compressed or expanded as the instrument table moved relative to the fixed reference surface. The analog dial gage can be read to 0.0001 inch. The dial-gage readings were not recorded electronically and therefore were read during site visits. The readings were used to check linear potentiometer drift and to apply corrections after adjustments to the extensometers.

Steven's Type-F chart recorders were used to record vertical deformation graphically to ensure data were collected if the linear potentiometer or the electronic data logger failed. Movement of the instrument table relative to the extensometer pipe was recorded by a drum rotating against a clock-driven pen (Riley, 1986). A counterweight, suspended from the gear train, balanced the chart drum against the force exerted on the recorder drive pulley by the extensometer pipe. Vertical-deformation data recorded on the chart can be read to 0.001 ft. The chart recorder can be operated for 32 days before the chart has to be replaced.

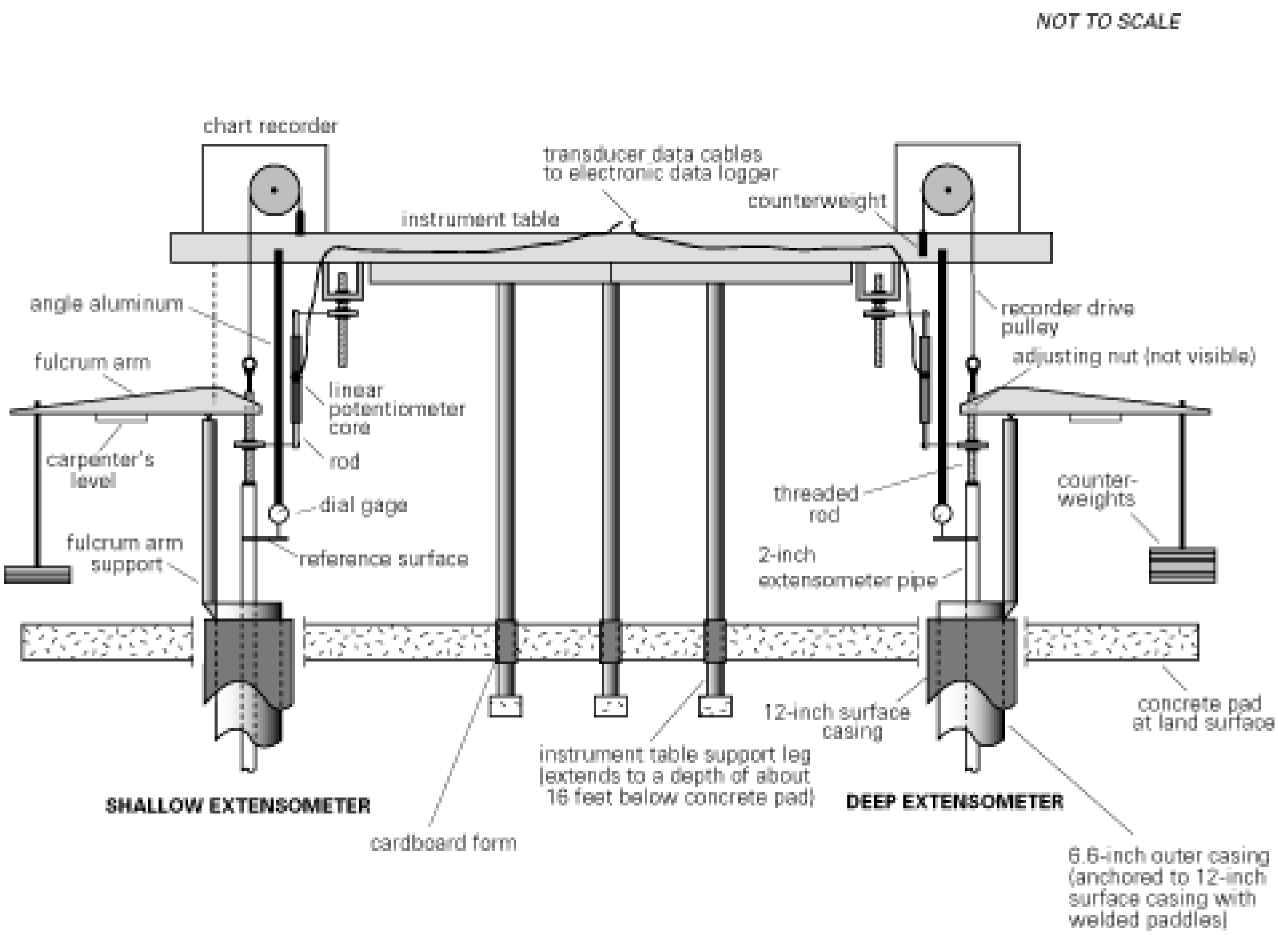
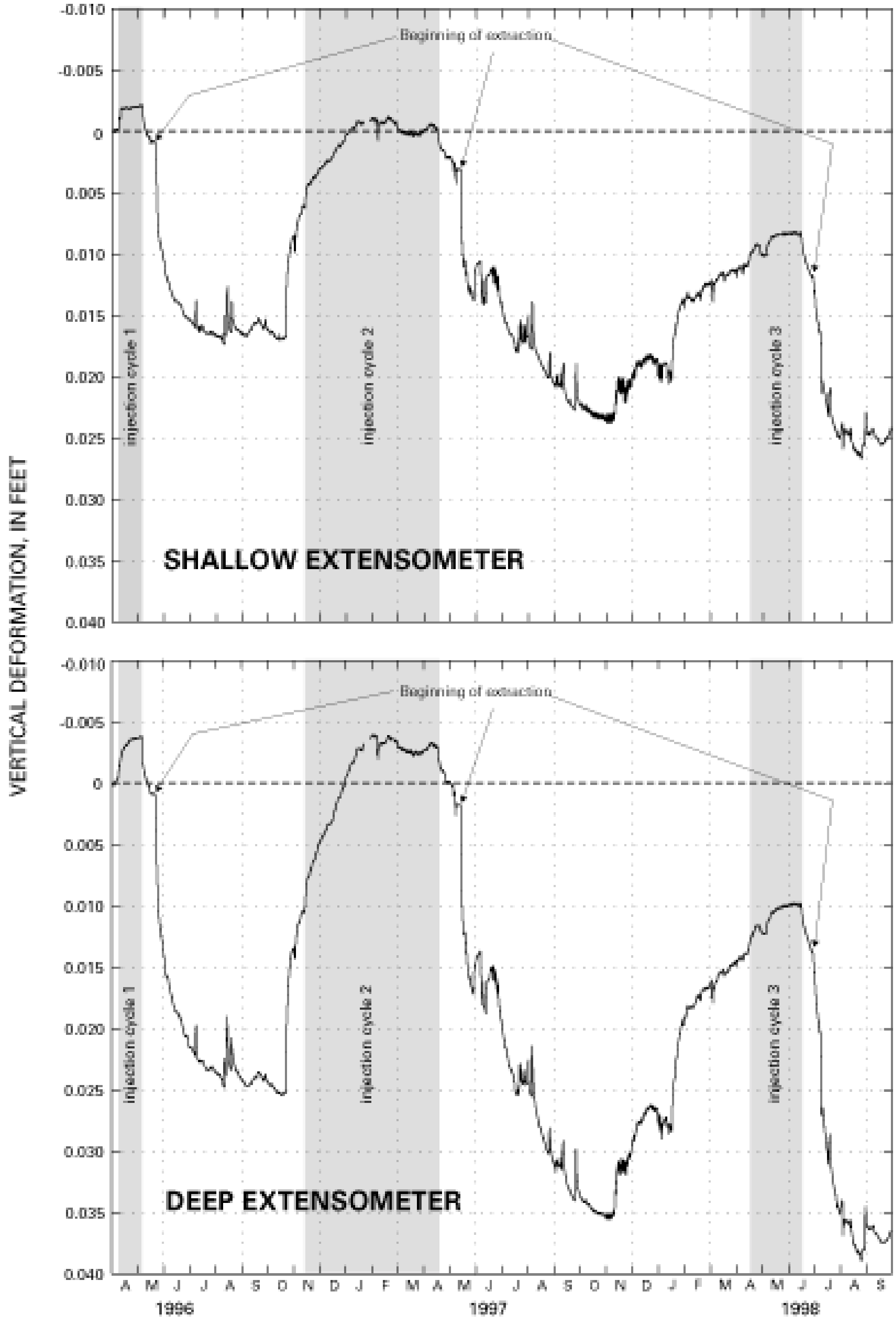


Figure 6. Above-ground installation of the dual extensometer at the Avenue K-8 and 5th Street West well field in Lancaster, Antelope Valley, California.



EXPLANATION

-------- Starting value of vertical deformation on first day of period of record

Figure 7. Vertical deformation of the aquifer system measured at the shallow (7N/12W-27F9) and deep (7N/12W-27F10) extensometers in Lancaster, Antelope Valley, California, April 1996 through September 1998.

Data Collection and Processing

Collection of vertical-deformation data began in early April 1996, after a series of load tests were done to calibrate the linear potentiometers. The load tests were done by adding and subtracting fixed increments of counterweights to the fulcrum arms and recording the changes in output from the linear potentiometers and analog dial gages. A generalized least-squares regression was applied to the load-test data to derive equation 1, which converts the potentiometer output (in millivolts) to vertical deformation (in feet):

$$VD = YI + (S)(RM), \qquad (1)$$

where

- VD is the computed vertical deformation, in feet;
- YI is the *y*-intercept of the least-squares regression equation, in feet;
- S is the slope of the least-squares regression equation, in feet per millivolt; and
- RM is the ratiometric output of the linear potentiometer at a specific time, in millivolts.

The *y*-intercept values derived from the load-test data for equation 1 for each extensometer were adjusted slightly to set the starting value of vertical deformation to zero on the first day of the period of record. The values of vertical deformation were cumulative to April 2 and April 3, 1996, for the deep and shallow extensometers, respectively.

Vertical deformation of the aquifer system was measured at the shallow (7N/12W-27F9) and deep (7N/12W-27F10) extensometers (fig. 7). The downward trends in figure 7 indicate compaction of the aquifer system, and the upward trends indicate expansion of the aquifer system. Positive values indicate net compaction relative to the first day of the period of record and negative values indicate net expansion.

Weekly to bimonthly field visits were made to the dual extensometer from April 1996 through September 1998. The frequency of the field visits was determined by the magnitude and rate of vertical deformation and by the data-logger recording interval specified during the previous field visit. Data were recorded at increasingly longer intervals because it was determined that fewer measurements would not decrease data quality. The recording interval ranged from 1 minute on the first day of the cycle 1 injection (April 8, 1996) to 15 minutes for the cycle 3 extraction (July 1, 1998).

Several tasks were done during each field visit. Data stored on the data logger were retrieved to a laptop computer and checked to ensure the extensometers were operating properly. The analog dial-gage and linear potentiometer readings were recorded and compared to evaluate the performance of the dual extensometers. Charts were replaced on the chart recorders. The data-logger clock was synchronized with Coordinated Universal time. During many of the field visits, the fulcrum arms of the dual extensometer were adjusted to maintain constant tension on the extensometer pipe.

On completion of each field visit, the data were entered into the USGS National Water Information System (NWIS) database. Computer programs in the NWIS database used equation 1 to convert the linear potentiometric ratios to feet. Datum and time-shift corrections were applied to the converted data to account for disturbances to the extensometer during field visits and linear potentiometer drift.

GROUND-WATER-LEVEL MONITORING

Water-level changes associated with direct well injection and extraction were monitored in a network of 13 active or abandoned production wells (including the two wells used for injection) and 10 nested piezometers located at three sites (fig. 8). The piezometers and most of the wells were within 2 mi of the injection site. Water levels were monitored in three wells (6N/12W-9H3, 12M2, and 16A2) within about 3 mi southward from the injection site; well 12M2 is more southeasterly, which is the general direction of ground-water flow (Carlson and others, 1998).

The construction data in table 1 show that most of the piezometers and production wells in the water-level monitoring network are screened (perforated) within the upper and middle aquifers, the zones of the direct well injections. Three piezometers (7N/12W-27F5, 27H5, and 27P5) were screened solely in the lower aquifer. One production well (7N/12W-27F3) was screened in all three aquifers. The construction data in table 1 show that the screened intervals of most of the piezometers are fairly short (20 ft), whereas the screened intervals of the production wells are fairly long (200 to 800 ft).

Construction of Nested Piezometers

Two sets of nested piezometers were constructed for the study, each containing four 2-inch wells in a single borehole. Boreholes were drilled using direct-rotary drilling methods (Lapham and others, 1997).

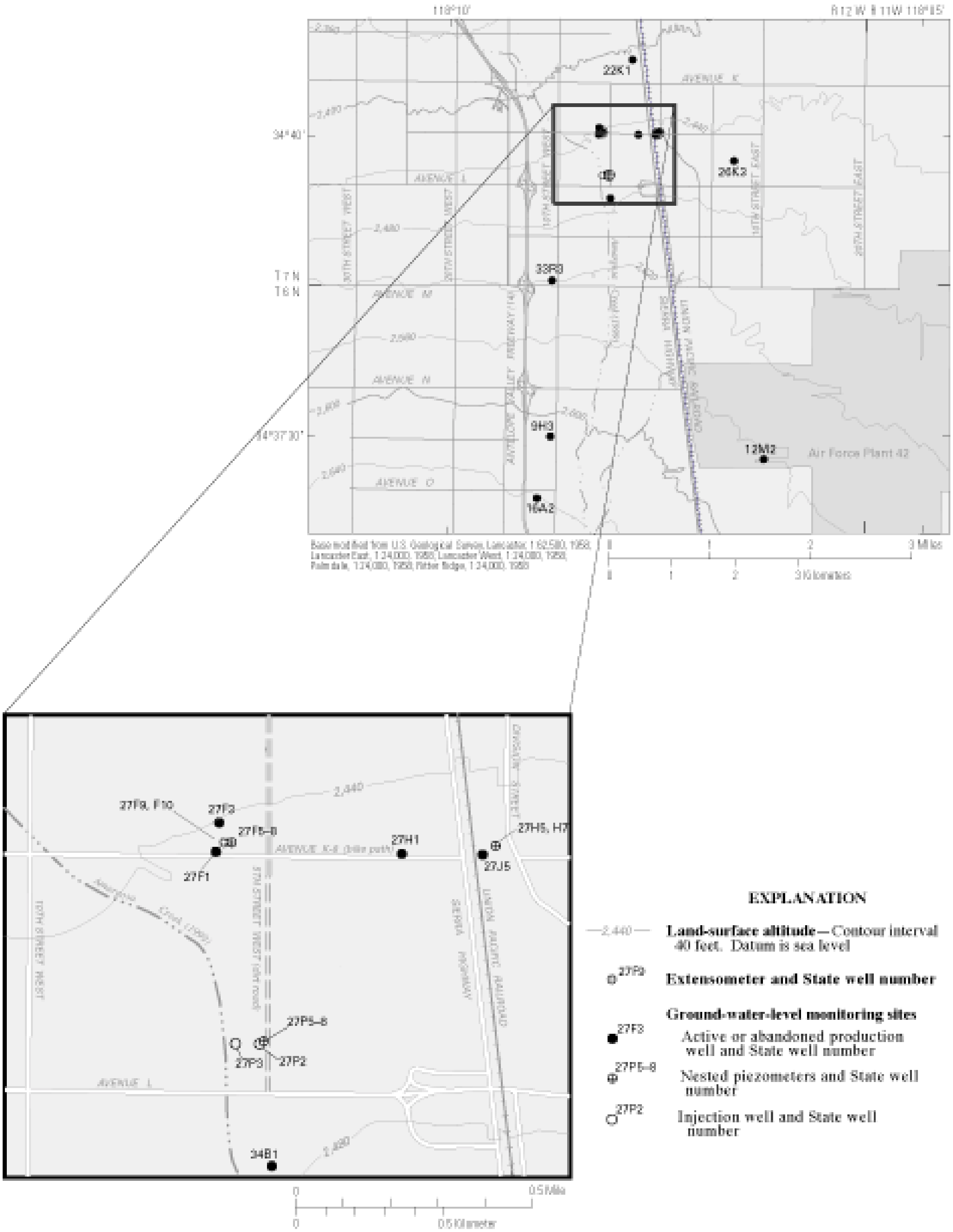


Figure 8. Locations of ground-water-level monitoring sites used for the injection, storage, and recovery study at Lancaster, Antelope Valley, California.

Table 1. Well-construction data for wells used in the injection, storage, and recovery study at Lancaster, Antelope Valley, California, September 1995 through September 1998

[State well number: See well-numbering system in text. Location of wells are show in figures 3, 8, and (or) 37. USGS, U.S. Geological Survey. USGS site identification number: The unique number for each site is based on the latitude and longitude of the site, which is referenced to the North American Datum of 1927 (NAD27). First six digits are latitude, next seven digits are longitude, and final two digits are a sequence number to uniquely identify each site. Altitude of land surface in feet above sea level. Use of well: AB, abandoned; EXTM, extensometer; INDS, industrial supply; PIEZ, piezometer; PS, public supply. Depth drilled, casing depth, and screened (perforated) interval in feet below land surface. Screened (perforated) intervals: depth of top and bottom of well screen or perforations; screened or perforated throughout entire interval unless denoted by asterisk (*). The extensometers and piezometers were installed by the U.S. Geological Survey. Aquifer zones: U, upper; M, middle; L, lower; UNK, unknown. Type of data included in this report for each well: BP, barometric pressure; C, compaction; F, flow; WC, water chemistry; WL, water level. —, no data]

State well number	USGS site identification number	Local well name	Altitude of land surface	Use of well	Year of construction	Depth drilled	Well casing		Screened interval depth	Aquifer zone perforated	Type of data included in this report
							Diameter (inches)	Depth			
6N/12W -9H3	343727118085202	—	2,610	PS	1992	1,015	16	910	500–900	M	WL
-12M2	343717118063601	DW8-1	2,560	INDS	1976	810	14	801	500–801	M	WL
-16A2	343655118090001	—	2,640	PS	—	([1])	—	([1])	—	UNK	WL
7N/12W-15R2	344123118075501	4-9	2,386	PS	1953	670	14	670	466–670	U, M	WC
-15R3	344130118075701	4-17	2,375	PS	1958	1,227	14	1,227	480–1,227*	U, M, L	WC
-15R4	344125118075801	4-26	2,384	PS	1965	700	14	693	235–693	U, M	WC
-21C2	344107118092401	4-12	2,357	PS	1955	639	14	639	300–639	U, M	WC
-21C4	344109118092601	4-25	2,359	PS	1964	800	14	640	200–640	U, M	WC
-21C5	344109118092201	4-38	2,358	PS	1974	750	16	733	210–720	U, M	WC
-22B2	344120118081301	4-5	2,375	PS	1947	578	14	552	192–552	U, M	WC
-22K1	344043118080301	—	2,407	AB	—	400	8	—	—	U	WL
-26K3	343951118065902	4-31	2,459	AB	1969	770	16	687	310–674	U, M	WL
-27F1	344004118082401	—	2,444	AB	—	—	—	([2])	—	UNK	WL
-27F2	344005118081801	4-43	2,445	PS	1988	1,210	16	1,202	400–1,202	U, M, L	WC
-27F3	344006118082601	4-44	2,440	PS	1988	1,220	16	1,202	400–1,202	U, M, L	WC, WL
-27F5	344005118082201	5K8-PZ1	2,441.6	PIEZ	1996	1,183	2	935	905–925	L	WC, WL, BP
-27F6	344005118082202	5K8-PZ2	2,441.6	PIEZ	1996	1,183	2	735	705–725	M	WC, WL
-27F7	344005118082203	5K8-PZ3	2,441.6	PIEZ	1996	1,183	2	535	505–525	M	WC, WL
-27F8	344005118082204	5K8-PZ4	2,441.6	PIEZ	1996	1,183	2	425	395–415	U	WC, WL
-27F9	344005118082205	5K8-EX1	2,441.6	EXTM	1996	735	7	725	—	—	C
-27F10	344005118082206	5K8-EX2	2,441.6	EXTM	1996	1,205	7	1,190	—	—	C
-27H1	344004118075901	—	2,449	AB	1949	500	14	500	189–500	U	WL
-27H3	344008118074701	4-33	2,443	PS	1971	730	16	710	260–700	U, M	WC
-27H5	344003118074801	DK8-PZ1	2,449	PIEZ	1992	1,120	2	1,120	1,080–1,100	L	WC, WL
-27H7	344003118074803	DK8-PZ3	2,449	PIEZ	1992	1,120	2	724	684–704	M	WL

See footnote at end of table.

Table 1. Well-construction data for wells used in the injection, storage, and recovery study at Lancaster, Antelope Valley, California, September 1995 through September 1998—Continued

State well number	USGS site identification number	Local well name	Altitude of land surface	Use of well	Year of construction	Depth drilled	Well casing		Screened interval depth	Aquifer zone perforated	Type of data included in this report
							Diameter (inches)	Depth			
7N/12W-27J4	344002118074701	4-13	2,448	PS	1956	1,108	14	[3]1,102	[3]362–1,102	U, M	WC
-27J5	343903118074801	4-8	2,449	AB	1953	700	14	700	350–700	U, M	WL
-27J6	344003118074901	4-42	2,449	PS	1987	1,174	16	1,150	400–1,140	U, M, L	WC
-27P2	343943118081801	4-32	2,463	PS	1969	735	16	727	282–717	U, M	F, WC, WL
-27P3	343943118082101	4-34	2,462	PS	1972	740	16	720	280–710	U, M	F, WC, WL
-27P5	343943118081701	5L-PZ1	2,462.7	PIEZ	1998	918	2	910	890–910	L	WL
-27P6	343943118081702	5L-PZ2	2,462.7	PIEZ	1998	918	2	560	540–560	M	WL
-27P7	343943118081703	5L-PZ3	2,462.7	PIEZ	1998	918	2	460	440–460	U	WL
-27P8	343943118081704	5L-PZ4	2,462.7	PIEZ	1998	918	2	390	330–370	U	WL
-30B1	344028118112601	4-37	2,387	PS	1974	652	16	610	260–600	U, M	WC
-33R3	343848118085203	—	2,519	PS	1993	824	16	780	440–760	U, M	WL
-34B1	343931118081601	—	2,475	AB	1953	425	8	—	—	U	WL
-34N3	343848118083801	4-29	2,522	PS	1967	792	14	740	350–728	U, M	WC
-34N4	343851118083801	4-30	2,517	PS	1968	800	16	770	350–760	U, M	WC

[1] Depth, obtained from owner, is approximately 800 feet below land surface.
[2] Depth at least 750 feet below land surface; sounded March 1996.
[3] Well casing filled with gravel to about 700 feet below land surface in early 1990s.

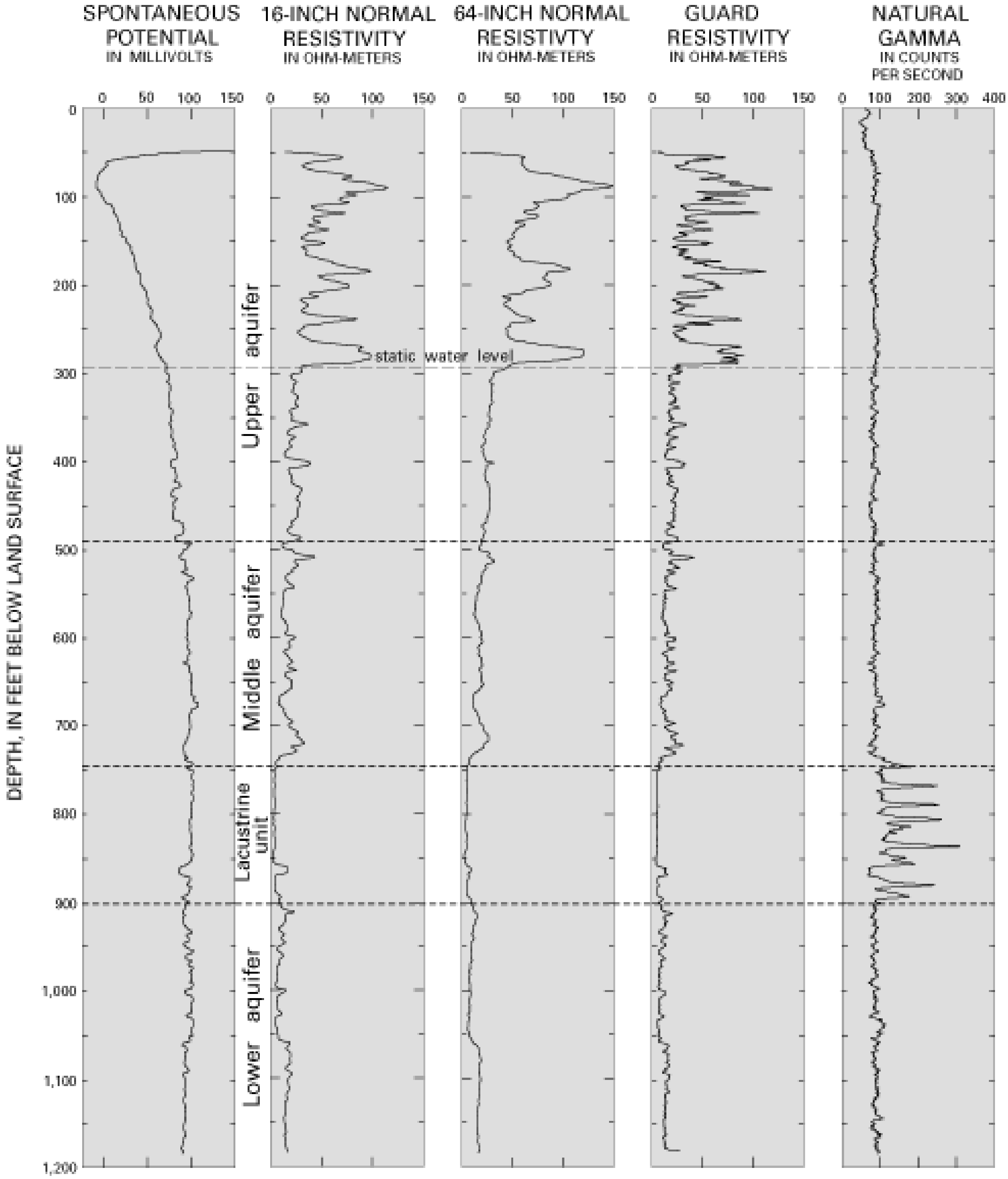


Figure 9. Geophysical logs, well-construction diagram, and lithologic log of the borehole for nested piezometers 7N/12W-27F5–8 at the extensometer site in Lancaster, Antelope Valley, California. The color of the samples are described using numerical color designations from Munsell soil-color charts (Munsell Color, 1975).

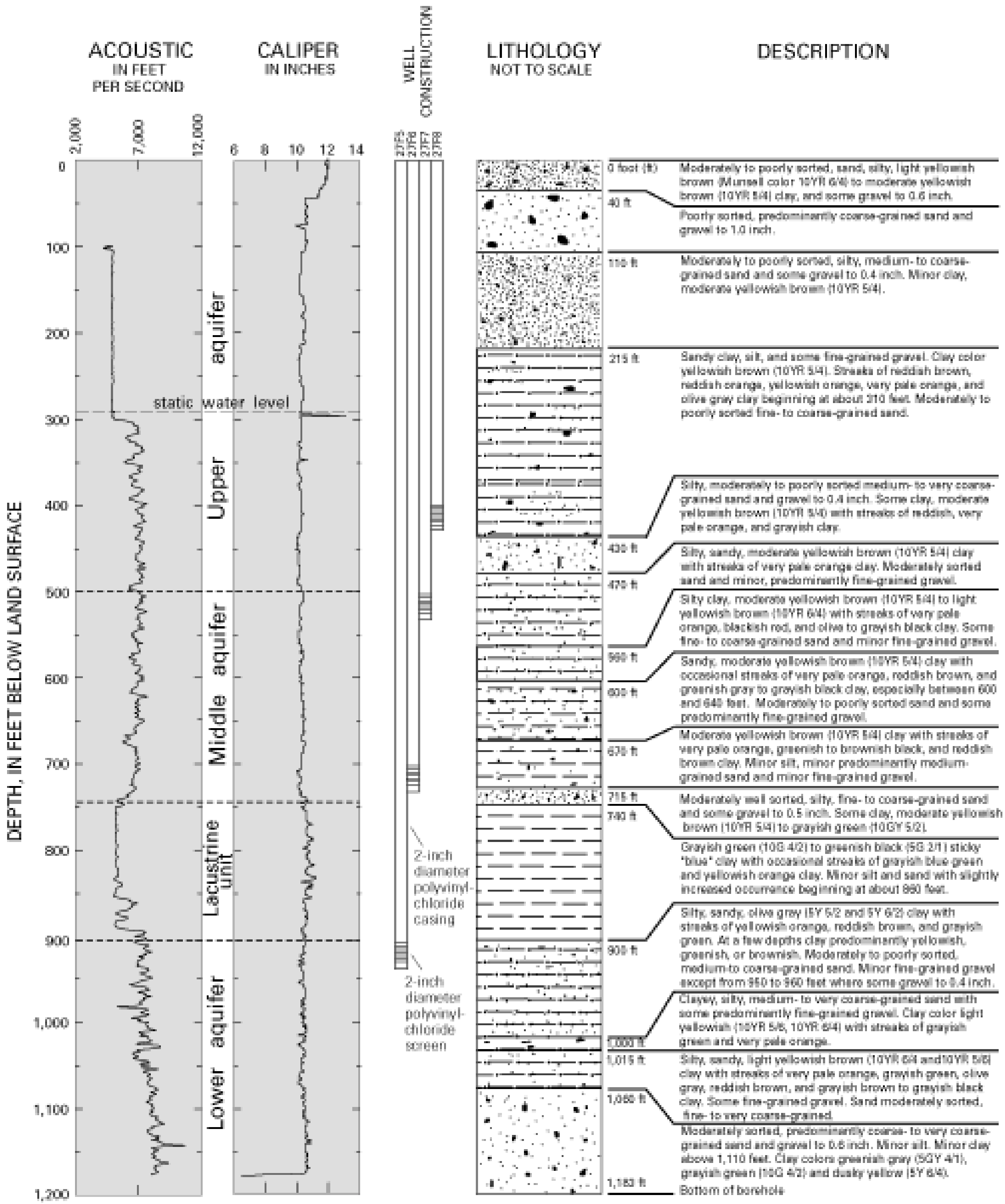


Figure 9.—Continued.

One set, wells 7N/12W-27F5–8, was installed in January 1996 adjacent to the extensometer (fig. 8) to monitor water-level changes in relation to vertical deformation of the aquifer system. The second set, wells 7N/12W-27P5–8, was installed in February 1998 approximately 80 ft northeast of well 7N/12W-27P2, the Avenue L and 5th Street West injection site (fig. 8). This set was installed near the injection wells to monitor water levels, help quantify the hydraulic properties of the aquifer system, and collect water-chemistry samples. Another set of nested piezometers (including 7N/12W-27H5 and 27H7) was installed in 1992 at the LACDPW Avenue K-8 and Division Street well field, about 0.66 mi northeast of the injection site (fig. 8).

As the boreholes were drilled, samples of cuttings, brought to the surface by circulating water-based drilling fluid, were collected approximately every 5 ft of the borehole depth. The drill cuttings from the borehole at the extensometer site were used to create a lithologic log for that site (fig. 9). Geophysical surveys were done for each site after the boreholes were drilled. Spontaneous potential, 16- and 64-inch normal resistivity, guard resistivity, natural gamma, acoustic and caliper logs were collected for the borehole at the extensometer site (fig. 9), and spontaneous potential, 16- and 64-inch normal resistivity, natural gamma, and caliper logs were collected for the borehole at the injection site (fig. 10). The logs were used to select the depth of each piezometer in the boreholes.

Construction data for each piezometer are listed in table 1 and shown in figures 11 and 12. The piezometers were assigned State and local well-identification numbers that correspond to the order of installation from deepest to shallowest. The piezometers were constructed with 2-inch diameter, schedule-40 or schedule-80 PVC casings and 20-foot long PVC screens; piezometer 7N/12W-27P8 was constructed with a 40-foot-long screen to reduce the chances of it going dry during extraction from the injection wells. A 12-inch diameter steel surface casing was installed at each site to prevent the infiltration of surface runoff.

Continuous Water-Level Measurements

Instrumentation

Submersible pressure transducers and data loggers (fig. 13) were installed in piezometers 7N/12W-27F5–8 at the extensometer site and 7N/12W-27P5–8 at the injection site (fig. 3) to continuously measure and record water levels. The transducers and data loggers were temporarily installed in 2 piezometers (7N/12W-27H5 and 27H7) and 1 abandoned production well (7N/12W-27J5) at the LACDPW Avenue K-8 and Division Street well field (fig. 3) to continuously measure and record water levels during injection cycles 1 and 2. The transducers were protected and secured within lockable metal or concrete storage enclosures positioned over the nested piezometers and abandoned production well. The transducers were suspended from threaded rods mounted across the top of the surface casing and secured to the rod with wire cable grips and heavy-duty, vinyl-coated cloth tape to prevent slippage.

The transducers in the piezometers at the extensometer site and at the Avenue K-8 and Division Street well field sites had a pressure range of 0 to 5 lb/in^2, equivalent to a submergence depth of 0 to 11.5 ft, and were accurate to 0.01 ft. The transducers used at the injection site had a pressure range of 0 to 30 lb/in^2, equivalent to a submergence depth of 0 to 69.3 ft below the water surface, and were accurate to 0.07 ft. Both sets of transducers were vented to atmospheric pressure. To prevent moisture from condensing in the vent tubes and affecting the measurements or potentially damaging the sensitive electronics of the transducers, the open, or land-surface, end of the transducer vent tubes were placed either in desiccant-filled film canisters or in aneroid bellows supplied by the manufacturer.

The transducers were calibrated at the time of installation to derive a relation to convert transducer output (in millivolts) to depth to water below land surface. Transducer output was recorded at fixed depths over at least one-half the pressure range of the transducer. At each depth, 1-minute readings of transducer output were recorded until three consecutive, nearly identical readings were obtained. The transducer was positioned and secured at its set point, a submergence depth within the calibration range. A generalized least-squares regression equation was applied to the calibration data and the following equation was derived to convert transducer output to depth to water below land surface (*DBLS*):

$$DBLS = SP - (S)(mV), \tag{2}$$

where

$DBLS$ is depth to water below land surface, in feet;

SP is the transducer set-point distance below land surface, in feet;

S is the slope of the least-squares regression equation, in feet per millivolt; and

mV is the recorded transducer output, in millivolts.

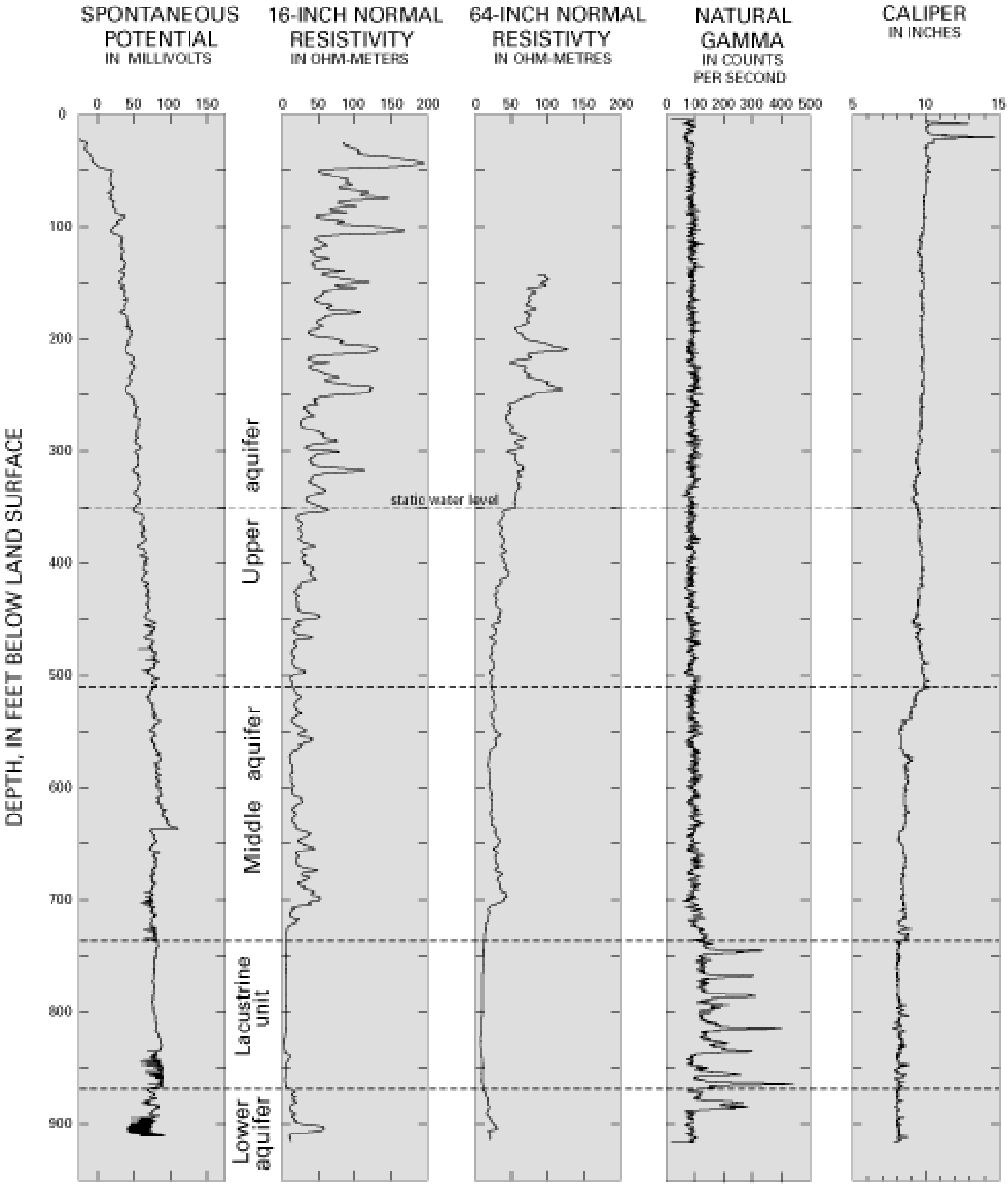


Figure 10. Geophysical logs of the borehole for nested piezometers 7N/12W-27P5–8 at the injection site in Lancaster, Antelope Valley, California.

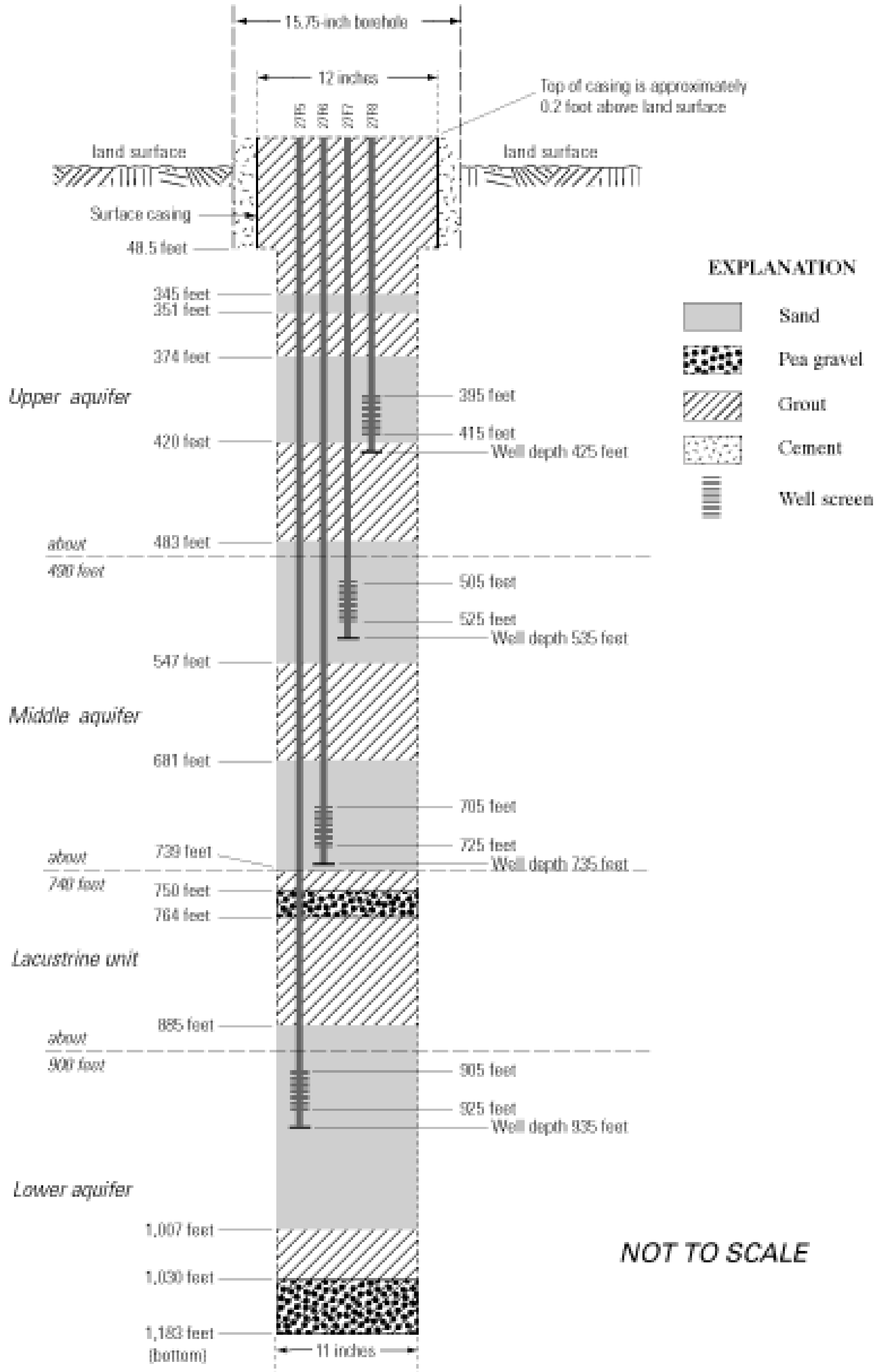


Figure 11. Well construction of nested piezometers 7N/12W-27F5–8 at the extensometer site in Lancaster, Antelope Valley, California.

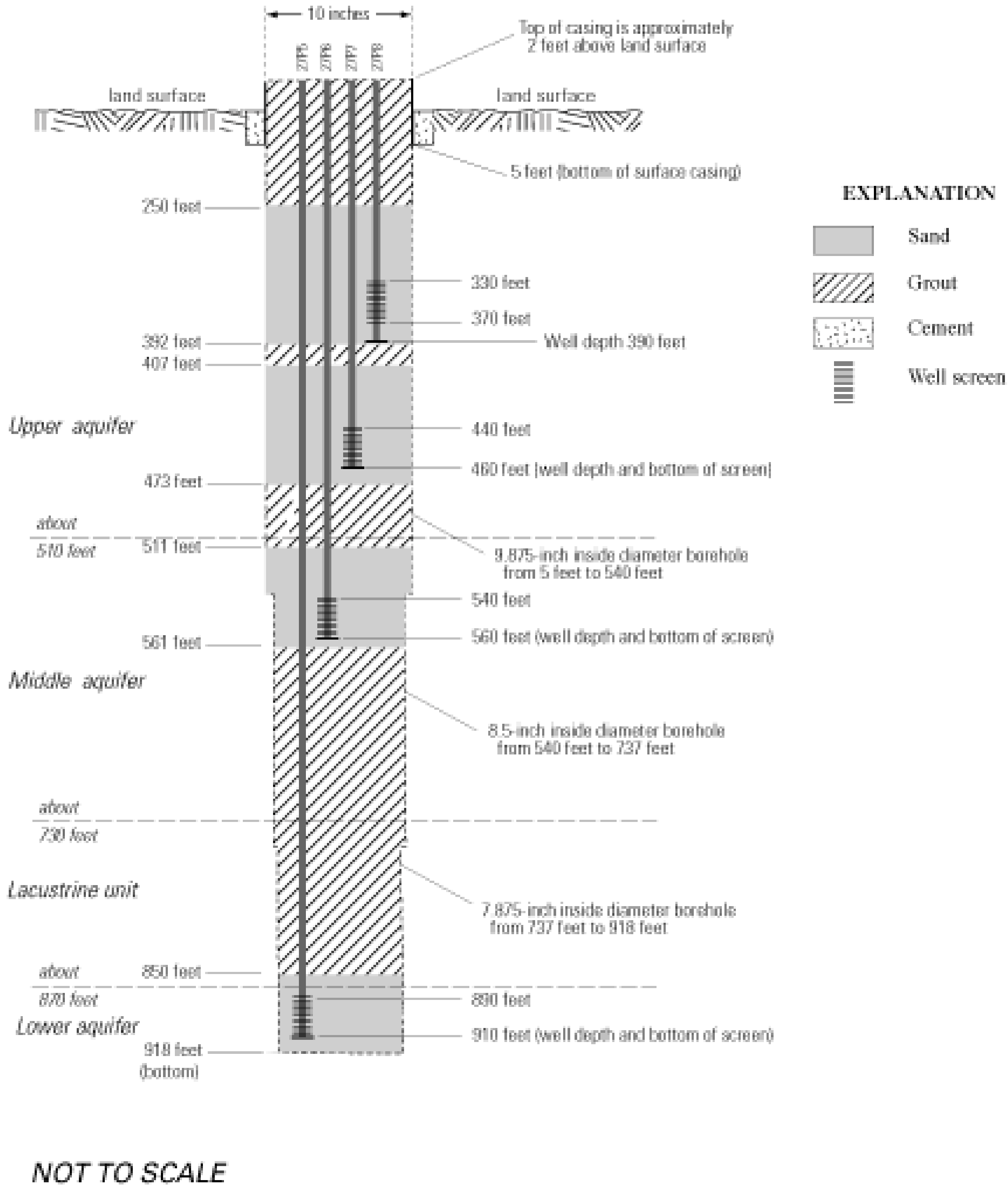


Figure 12. Well construction of nested piezometers 7N/12W-27P5–8 at the injection site in Lancaster, Antelope Valley, California.

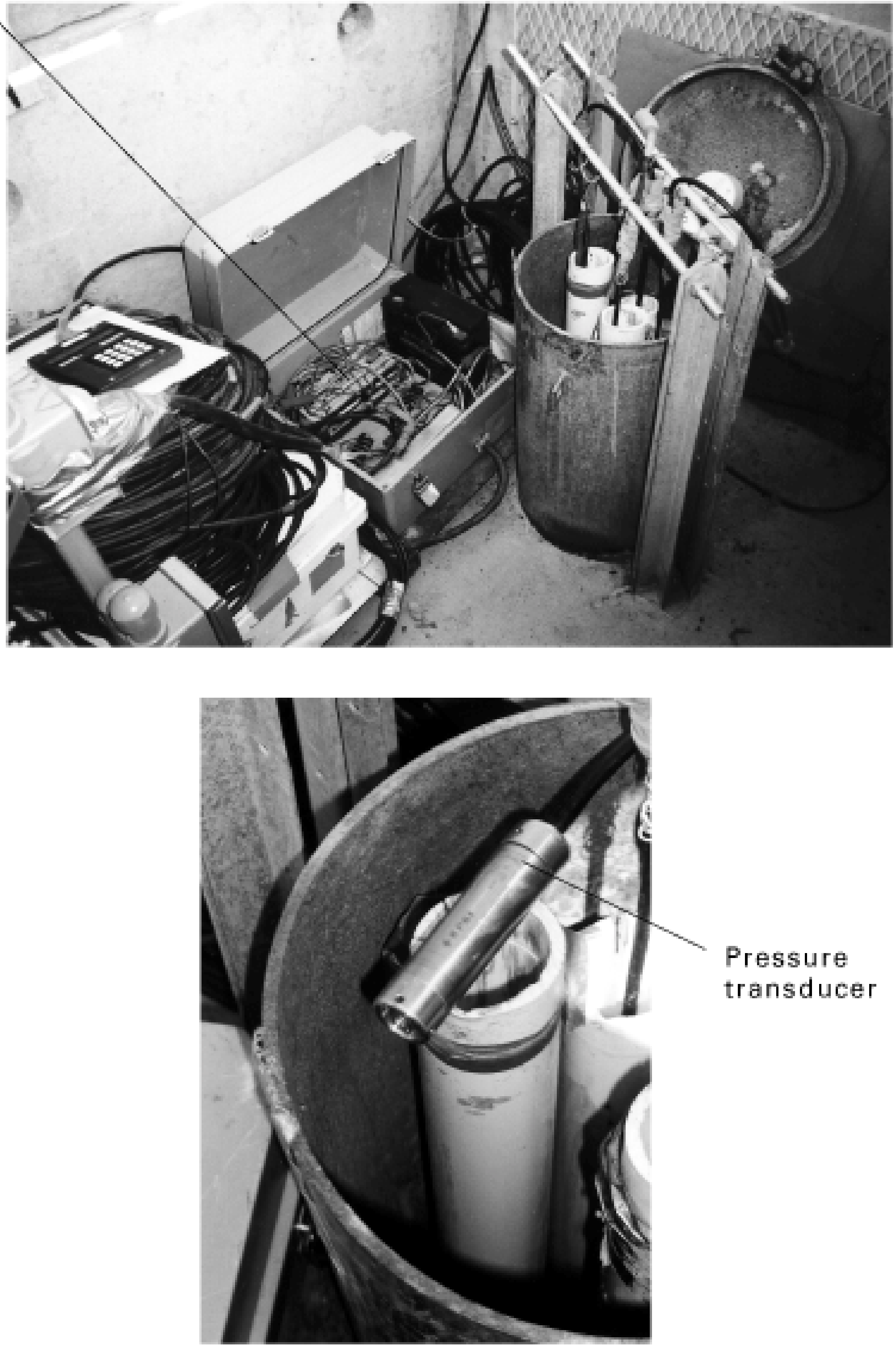


Figure 13. Typical pressure transducer and data-logger system used for recording continuous ground-water levels.

Barometric pressure was recorded at the extensometer site using an electronic pressure transmitter with a range of 600 to 1,600 millibars (fig. 14). Barometric pressure was not recorded at any specific well or piezometer but was assigned to piezometer 7N/12W-27F5 for the purpose of recording the data in the U.S. Geological Survey Automated Data Processing System (ADAPS) database. The data were used to evaluate the effect of barometric pressure on water levels and to monitor transducer performance. Water-level changes in deep wells normally are out of phase with barometric pressure changes because of the time it takes for air to move through the unsaturated zone. Continuous water-level data for deep wells that are in-phase with barometric pressure indicate either that the transducer vent tube is plugged or that the transducer has depressurized (Rummler, 1996).

Data Collection and Processing

Weekly to bimonthly field visits were made to the transducers from April 1996 through September 1998. Water-level and barometric-pressure data were downloaded from the data loggers to a laptop computer and checked to evaluate transducer performance. Water levels were measured with a calibrated electric tape and compared with water levels measured by the transducers; differences are attributed to transducer drift or to extraneous factors such as cable slippage.

The transducers periodically were recalibrated or repositioned during field visits. The transducers that had a fairly high cumulative drift (plus or minus 0.5 ft for a period of 6 months) were recalibrated using the same procedure applied during the initial installation. The transducers were frequently repositioned without

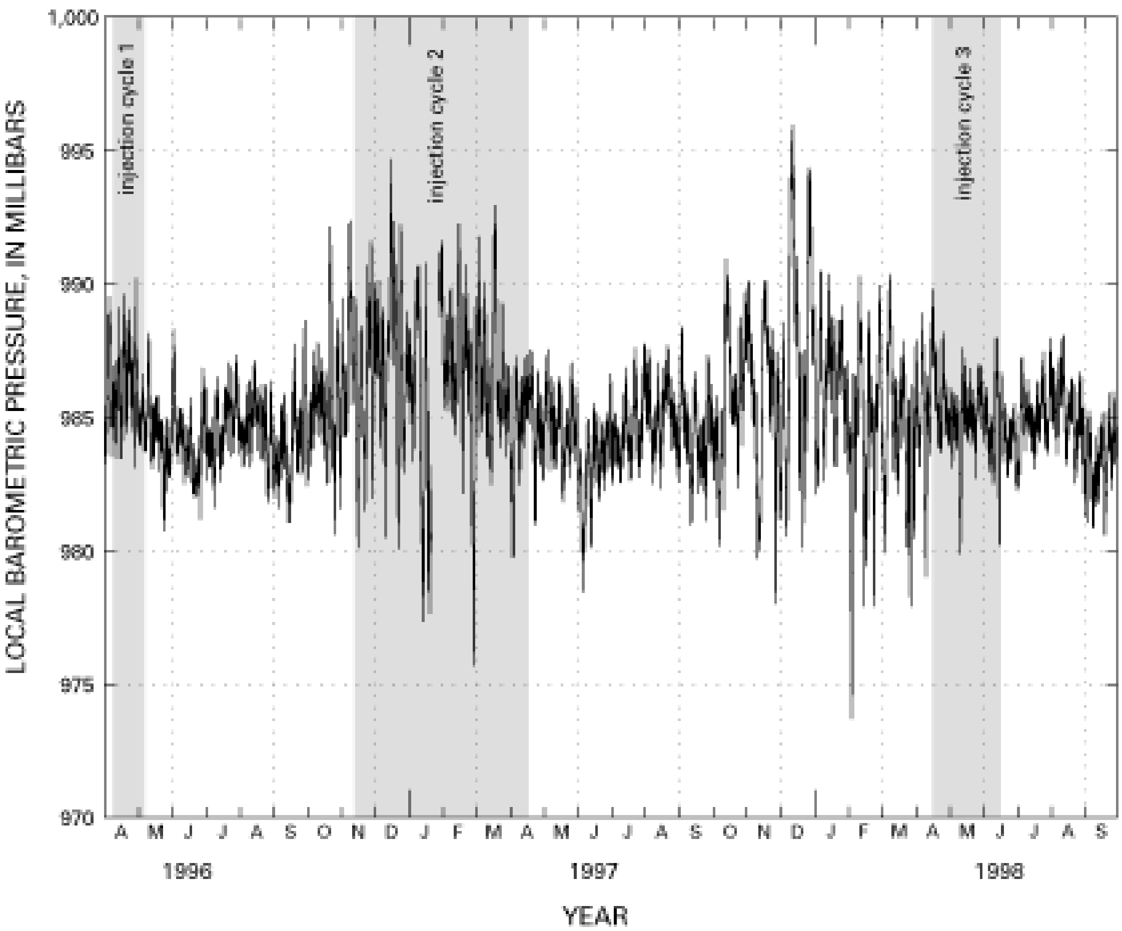


Figure 14. Local barometric pressure at the extensometer site in Lancaster, Antelope Valley, California, April 1996 through September 1998.

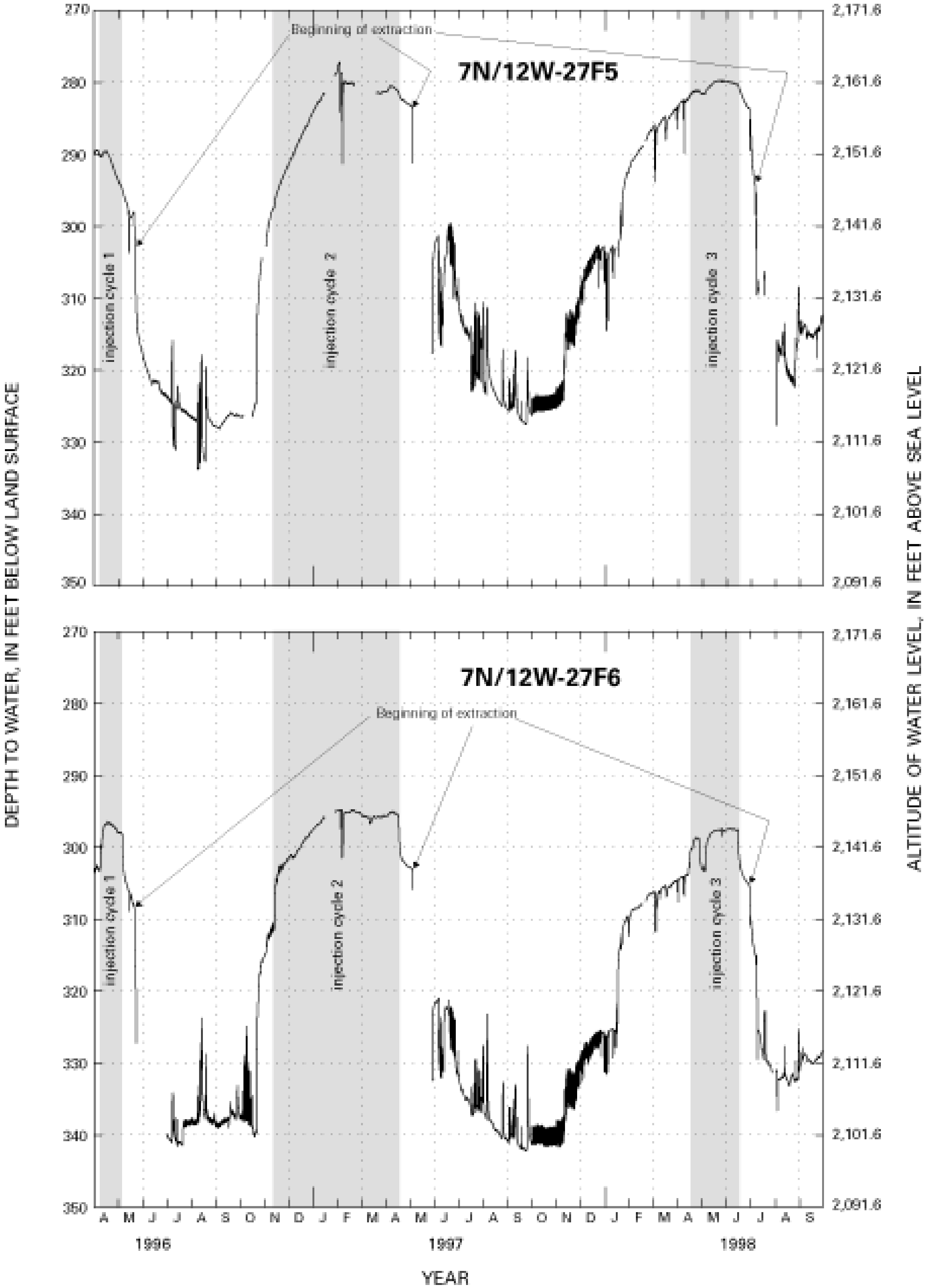


Figure 15. Ground-water levels recorded in piezometers 7N/12W-27F5–8 at the extensometer site in Lancaster, Antelope Valley, California, April 1996 through September 1998.

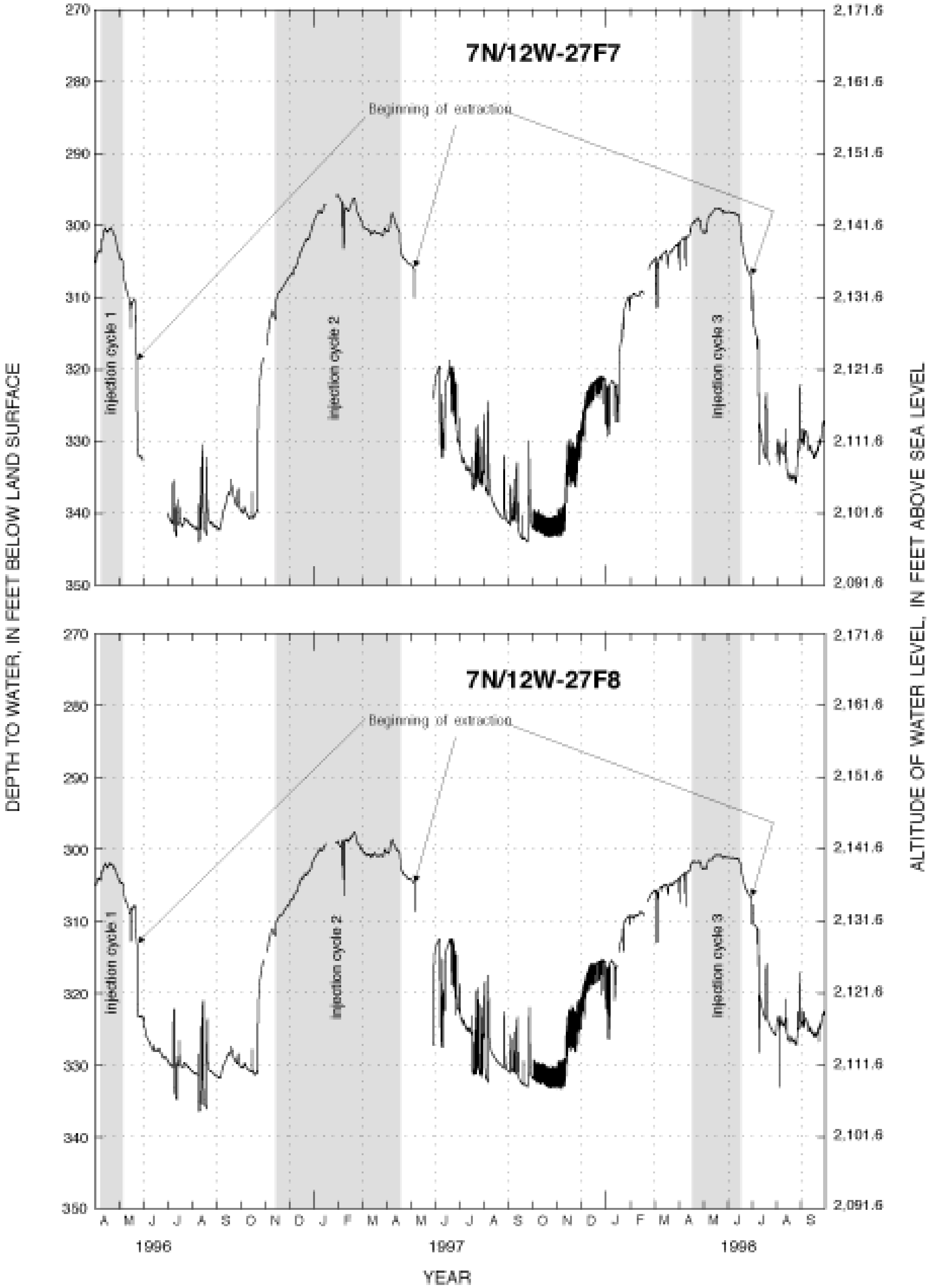


Figure 15.—Continued.

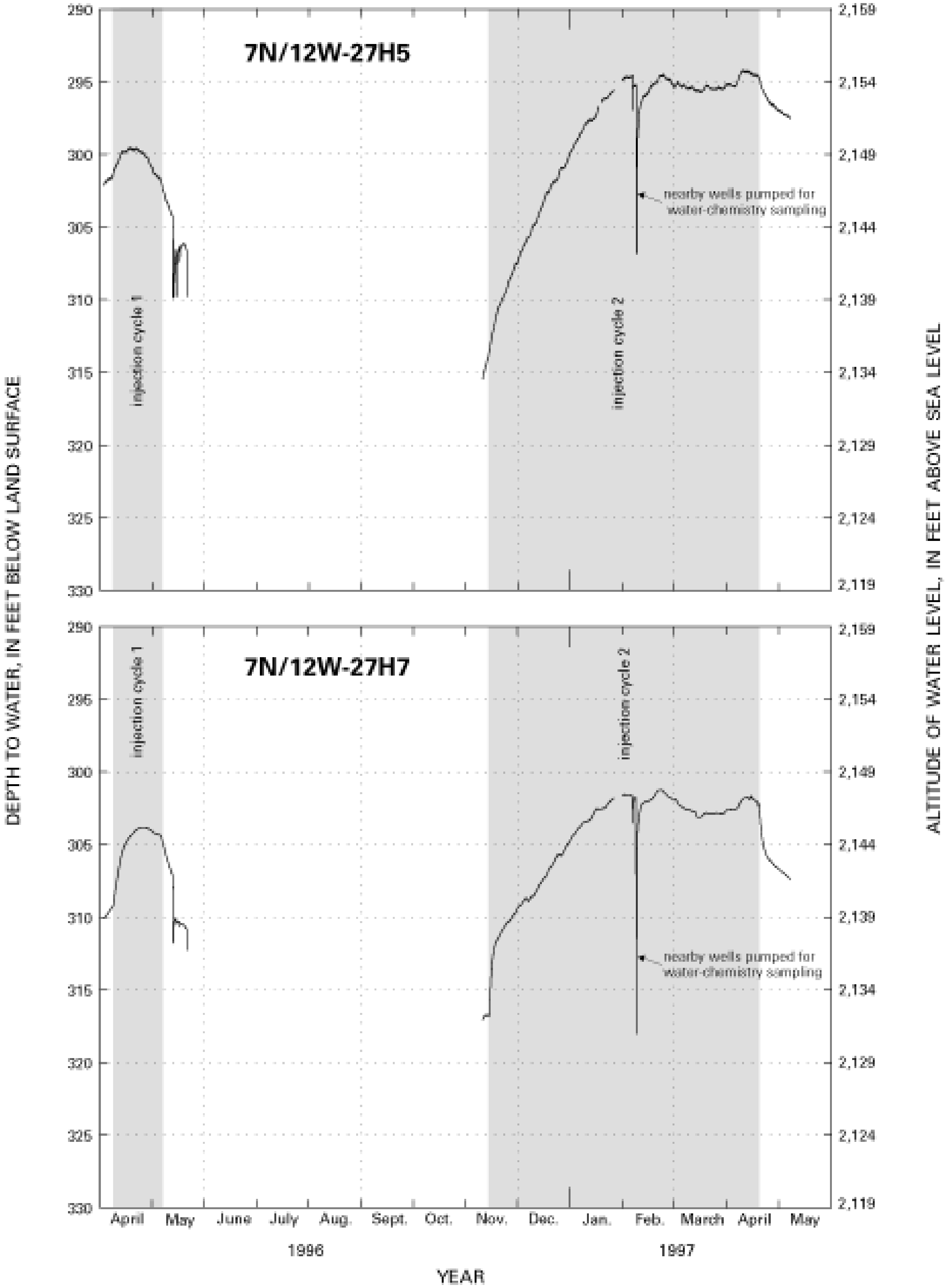


Figure 16. Ground-water levels recorded in piezometers 7N/12W-27H5 and 27H7 at the Avenue K-8 and Division Street well field in Lancaster, Antelope Valley, California, April 1996 through May 1997.

calibration to adjust for seasonal fluctuations in water levels. The repositioned transducers were not recalibrated because only the set point changed.

The continuous water-level data were processed and stored in the USGS NWIS database. Computer programs in the NWIS database were used to convert the transducer output (in millivolts) to depth to water below land surface using the equation derived from the calibration data. A datum correction was applied to the converted data to account for transducer drift.

Continuous water-level data are shown in figures 15–18. As these time-series plots show, there are many gaps in the recorded data. Some gaps represent periods when water levels declined below the set points of the transducers. Recording of the water-level data usually resumed when the transducer was repositioned during the next field visit. Other gaps may be due to power failures (including failures of backup batteries), temporary removal of a transducer for water-chemistry sampling, or transducer failure. Pumping at three of the production wells at the Avenue K-8 and Division Street well field during the summer and autumn resulted in water levels that exceeded the length of the transducer cables in piezometers 7N/12W-27H5 and 27H7. The transducer installed in piezometer 7N/12W-27P7 failed after operating for less than 1 month and was not replaced. Any water-level data recorded for this piezometer are not included in this report.

Periodic Water-Level Measurements

Water levels were periodically measured in abandoned and active production wells where it was not feasible or desirable to install transducers for the continuous measurement of water levels. Water levels also were periodically measured in injection wells 7N/12W-27P2 and 27P3, but only during cycles 1 and 2. Water levels were not measured in the injection wells

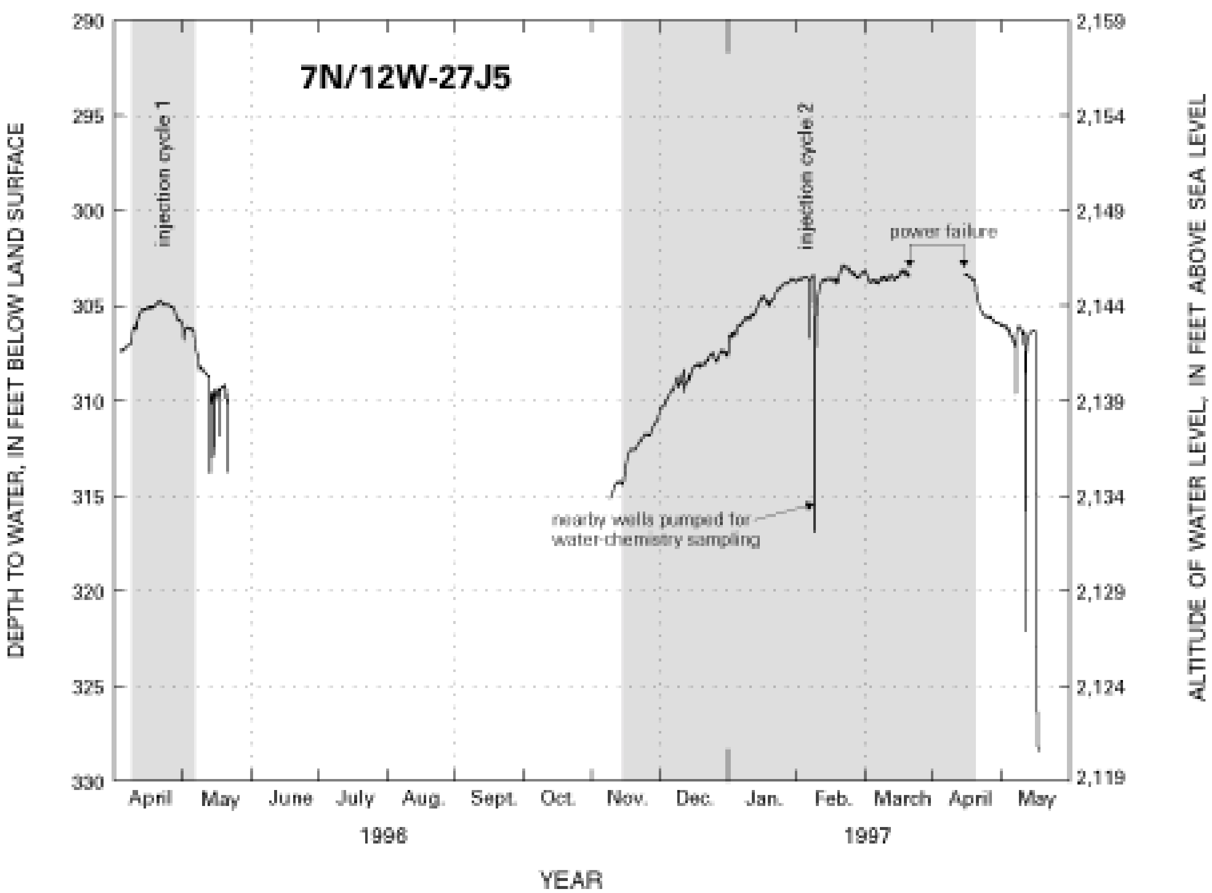


Figure 17. Ground-water levels recorded in abandoned production well 7N/12W-27J5 at the Avenue K-8 and Division Street well field in Lancaster, Antelope Valley, California, April 1996 through May 1997.

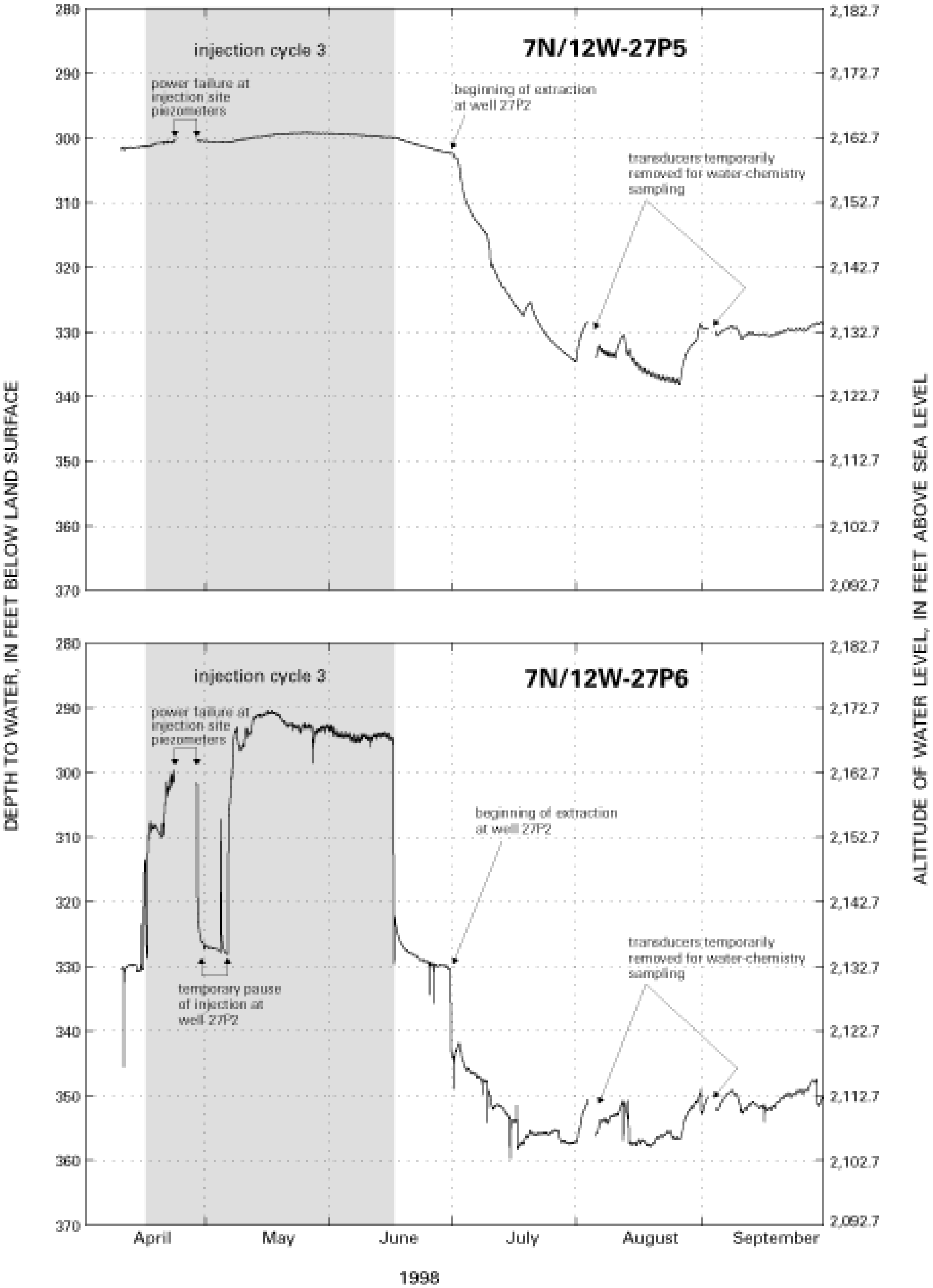


Figure 18. Ground-water levels recorded in piezometers 7N/12W-27P5, 27P6, and 27P8 at the injection site in Lancaster, Antelope Valley, California, April 1998 through September 1998.

during cycle 3 because the measuring points on these wells changed as a result of maintenance work.

Water levels in most of the wells were measured with a 500-foot calibrated electric tape with graduations of 0.01 ft; water levels in the remaining wells were measured using a graduated steel tape. The electric tape was used to measure most of the water levels because depth to water often exceeded 250 ft and measurements with a steel tape would have required more time. In some of the wells, measuring water levels with a steel tape would have been difficult owing to wet casings caused by condensation or cascading water. Water levels measured with both the electric tape and the steel tape generally were recorded to 0.01 ft, but are reported to the nearest 0.1 ft in table 2. Water levels were measured at least twice for each well to ensure that the initial measurement was read and recorded correctly.

All periodic water-level data were stored in the USGS NWIS database. Water levels measured in nested piezometers and production wells within 2 mi of the injection site during periods of direct well injection were assigned a status code of “Z” in the database to denote direct well injection at the time of measurement. Periodic water-level measurements listed in table 2 also are given in figure 19 for all wells and piezometers except for piezometers 7N/12W-27F5–8 and 27P5–8.

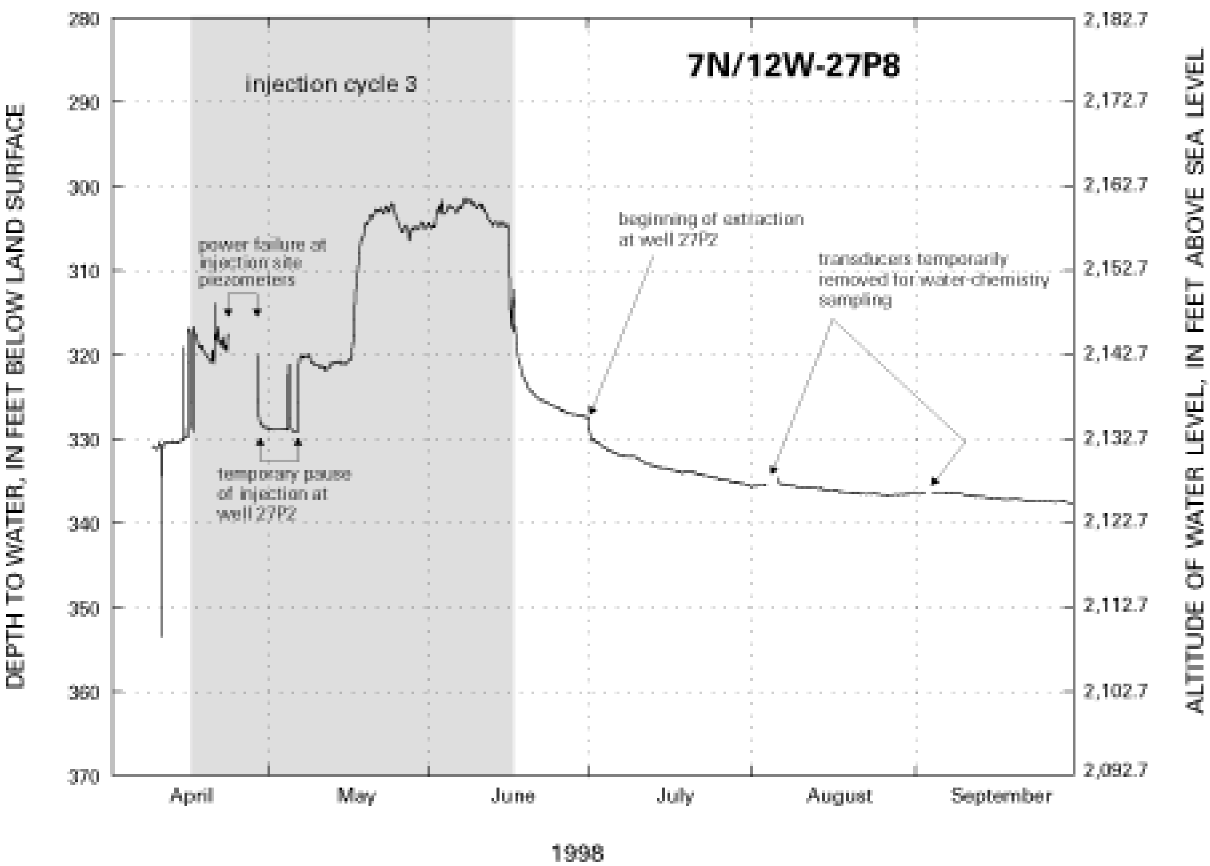


Figure 18.—Continued.