MICROGRAVITY SURVEYS

Temporal microgravity data were collected from a gravity-station monitoring network during the cycle 2 and cycle 3 injection phases. The data were used to estimate the three-dimensional shape of ground-water mounding near the injection site. The microgravity surveys were done as an alternative to installing many additional monitoring wells for measuring ground-water levels.

The gravity-station network consisted of 37 permanent gravity stations within 1 mi of the injection site (fig. 20). The gravity stations were areally distributed to measure the anticipated three-dimensional shape of ground-water mounding around the injection wells. Stations were placed in closely spaced arrays of four orthogonal spurs around the injection wells to define the slope of the ground-water mound. The first and second stations in each array were spaced 50 ft apart, the third station was spaced about 100 ft from the second, and the fourth station was spaced about 200 ft from the third. Additional stations were established at greater distances from the injection site where access permitted.

Gravity Station Construction

The gravity stations for the monitoring network were constructed to provide stable surfaces for use in future repeat surveys. Stations were constructed by auguring a 15-inch diameter hole approximately 3 ft deep. Three pieces of steel rebar 5/8 inch in diameter and 3 ft long were driven into the sides of the hole at 120-degree intervals to provide lateral stability to the native material (fig. 21). The hole was backfilled with 3.7 cubic feet (ft^3) of concrete in a continuous pour. Near the end of the pour, a 12-inch diameter cardboard tube was pushed into the concrete until it contacted the rebars. The remainder of the cardboard tube was filled with concrete so that the final top surface was about 1 inch above land surface. Approximately 15 minutes after the concrete was poured, three 2-inch diameter bronze tablets were placed into the top of the wet concrete using a template of the gravity meter legs. Bronze tablets were used because of their low coefficient of thermal expansion. One of the three bronze tablets was stamped with the station identifier (a short alpha-numeric designation) and with a central divot to accommodate the reference leg of the gravity meter. This reference leg tablet was placed in the northwest quadrant of all stations. The other two tablets were positioned so that the two cross-level legs (the two legs closest together) were oriented true north. Orienting the two cross-level legs true north eliminated the possibility of a regional magnetic field differentially affecting the nulling device of the gravity meter. After the concrete dried, divots were drilled into the other two tablets using the template of the gravity meter legs.

The Quartz Hill bedrock reference station (fig. 3) was constructed using an existing USGS bench mark installed on Quartz Hill in 1989. The central divot in the bench mark was used as the reference leg position. The remaining two leg rests, aligned true north, were constructed by star drilling 1/2-inch holes into the crystalline rock. The holes were filled with lead and a concave head tack was hammered into the lead.

Gravity Data Collection

Gravity was measured relative to the Quartz Hill reference station (QTZ) about 3.6 mi west-southwest of the injection site. QTZ is on crystalline bedrock and was far enough from the injection site so that mass changes from injected water would not affect gravity. A secondary reference station (GR) was established near the injection site to reduce travel time between QTZ and the gravity stations. GR is approximately 500 ft east of well 7N/12W-27H1, which allowed gravity changes to be correlated with water-level changes. Mass changes from injected water were expected to be minimal because GR was hydraulically upgradient of the injection site (James Howle, U.S. Geological Survey, written commun., 2000).

A LaCoste and Romberg (L and R) Model D gravity meter (serial number D79) was used for this study. The gravity meter is equipped with an electrostatic nulling device (fig. 22) to obtain microGal accuracies. An electronic data logger read filtered output voltage from the electrostatic nulling device at 3-second intervals. The mean output voltage (for 20 measurements) and standard deviation were recorded at 1-minute intervals. Barometric pressure, measured by an electronic barometer, also was recorded at 1-minute intervals. Detailed descriptions of the pre-survey checks, the process of making gravity measurements, and the sources of survey error are provided in appendixes A, B, and C, respectively.

Three surveys (prior to injection, midway through injection, and near the end of injection) were made during cycle 2, and two surveys (prior to injection and near the end of injection) were made during cycle 3 (tables 3 and 4). All five surveys were completed using three sequential steps. During the first step, the difference in gravity between the QTZ reference station and the GR reference station near the injection site was determined. During the second step, gravity was measured for groups of three or four stations at a time

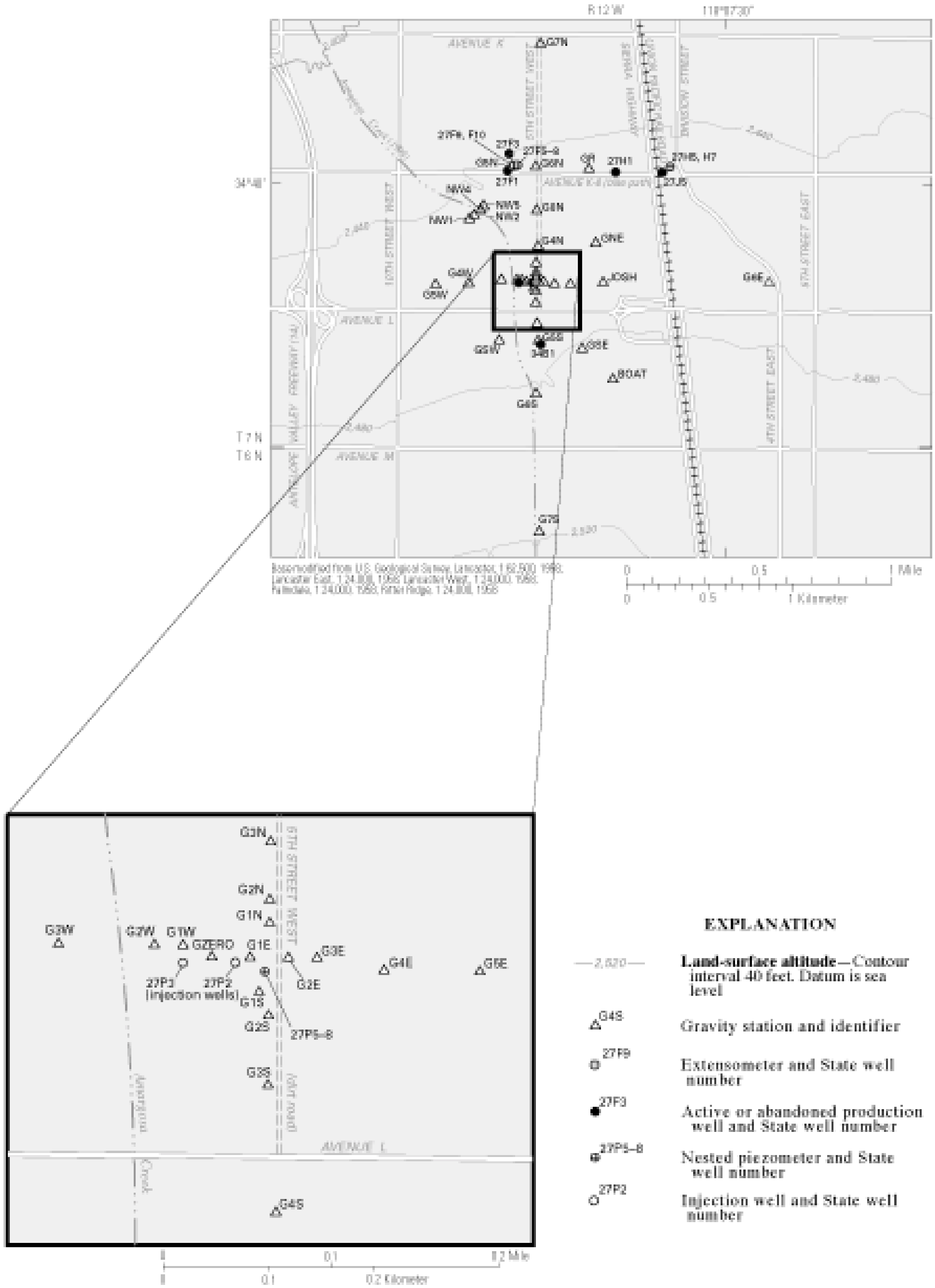

Figure 20. Locations of gravity stations used for the injection, storage, and recovery study at Lancaster, Antelope Valley, California.

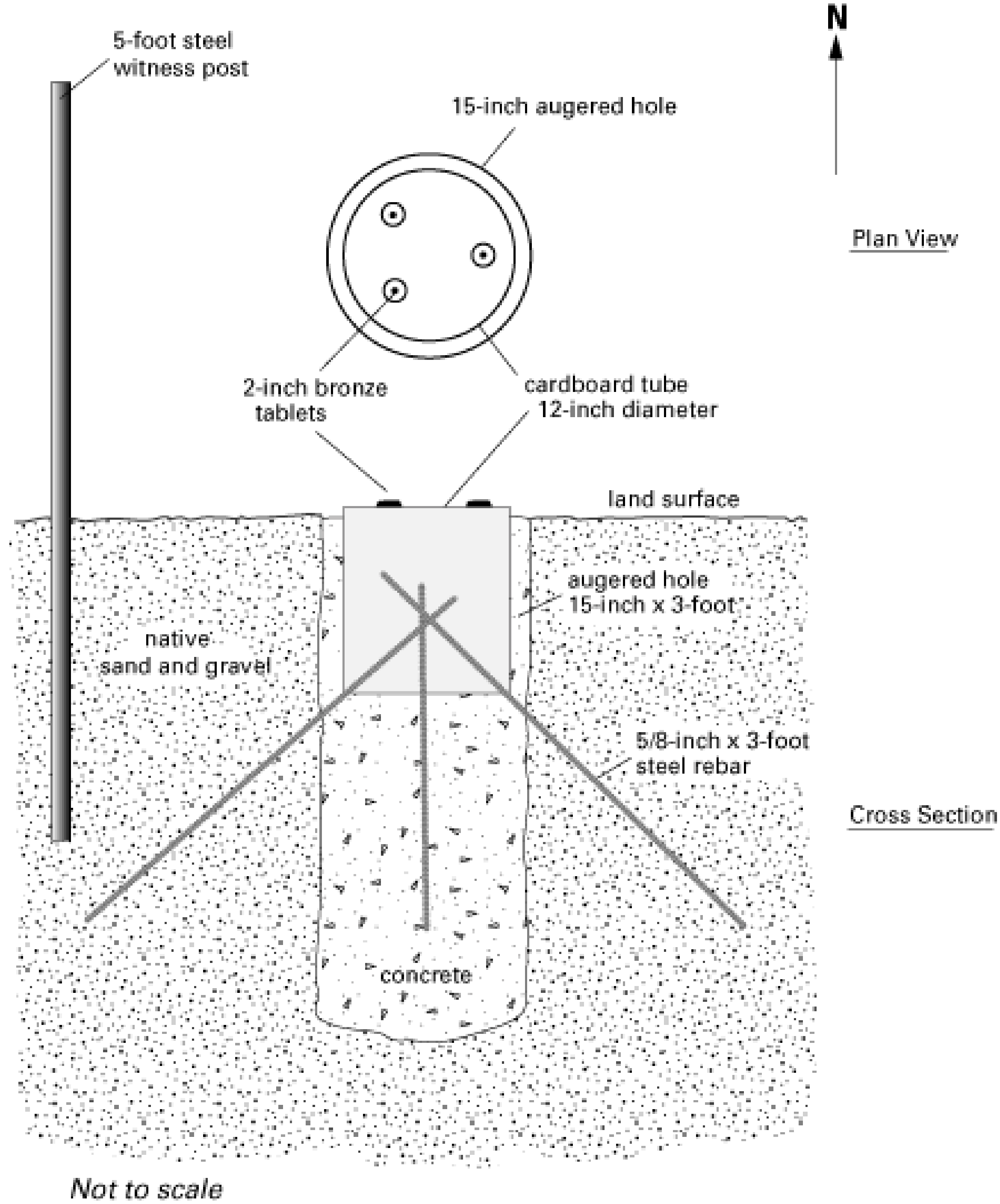

Figure 21. Gravity station construction.

in a closed loop configuration that began and ended at the GR reference station. Each station loop was completed twice resulting in two gravity measurements for each gravity station and three gravity measurements for the GR reference station. Multiple gravity measurements were made at each station to evaluate instrument drift during the survey and to assess the repeatability and accuracy of the measured differences in gravity. During the third step, the total difference in gravity between the stable bedrock and the gravity stations was calculated by adding the difference in gravity between the QTZ and GR reference stations to the difference between the GR reference station and any other station.

The gravity stations were interspersed among the second-order vertical-control bench marks established for this study to monitor possible land-surface elevation changes (see "Geodetic Monitoring" section). The gravity stations and vertical-control bench marks were leveled simultaneously during each differential-leveling survey. It was critical to have vertical control during the injection period to ensure that any changes in gravity were caused by changes in aquifer mass and not by changes in station altitude owing to aquifer-system deformation.

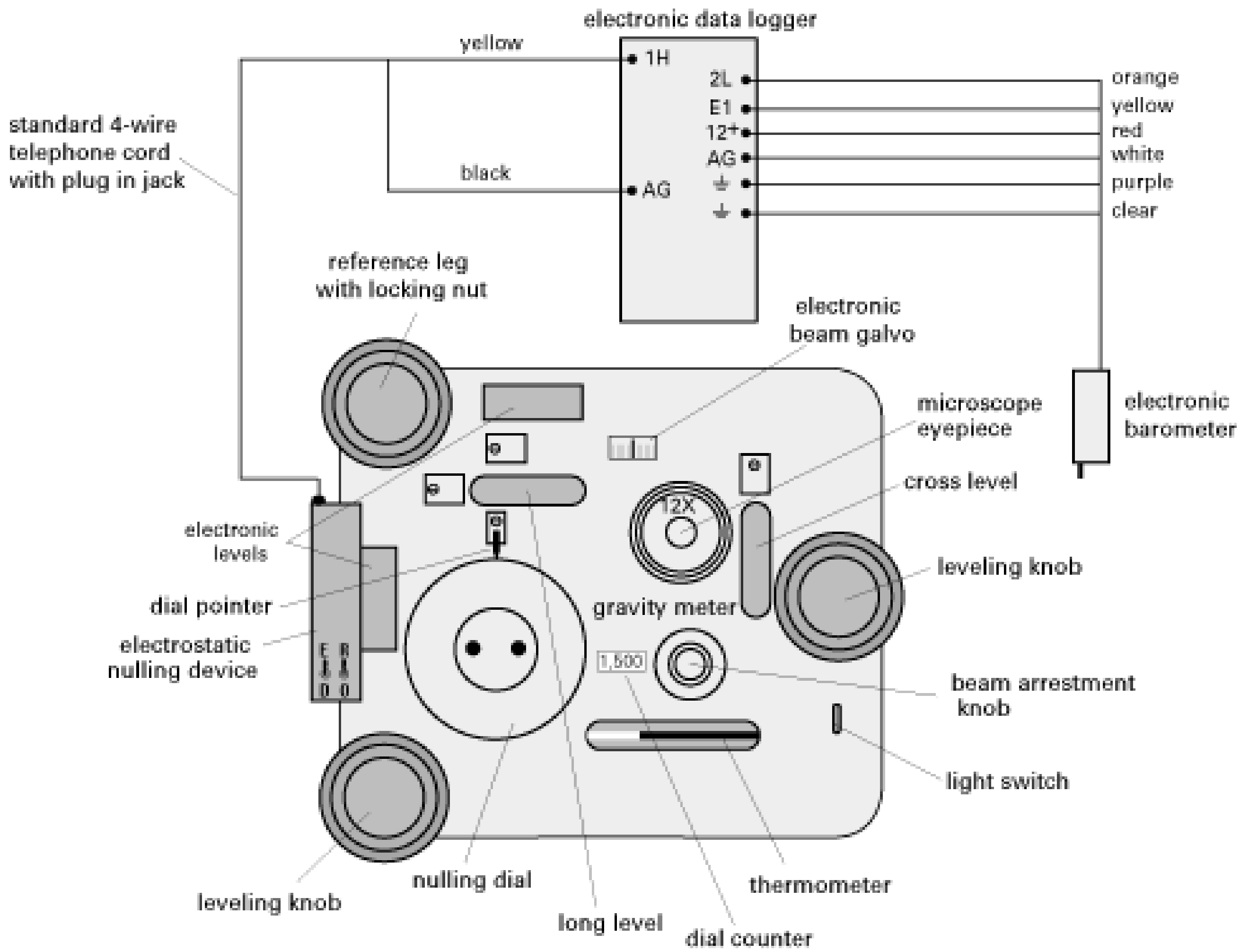

Figure 22. Top view of a LaCoste and Romberg Model D gravity meter and schematic wiring diagram of an electronic data logger and barometer.

Table 3. Microgravity data collected during cycle 2 of the injection, storage, and recovery study at Lancaster, Antelope Valley, California, November 1996 through April 1997

[Latitude and longitude are referenced to the North American Datum of 1983 (NAD83), determined using GPS in 1996–97. Gravity measured relative to Quartz Hill bedrock reference station 3.6 miles from injection site (fig. 3). Station altitudes are referenced to the National Geodetic Vertical Datum of 1929 (NGVD29) and were measured by leveling to second-order standards of accuracy. Altitudes for the pre-injection survey were measured during November 4–13, 1996, and for the near-completion of injection on April 9, 1997, unless indicated otherwise (see footnotes). mGal, milliGal; µGal, microGal; mm, millimeter. $\bar{x}$, mean. —, no data]

Gravity station identifier (fig. 20)	Latitude	Longitude	Pre-injection survey (November 5–9, 1996)				Mid-injection survey (January 29–February 1, 1997)		Change in microgravity from previous survey (µGal)
			Mean change in microgravity (mGal)	Standard deviation (µGal)	Station altitude		Mean change in microgravity (mGal)	Standard deviation (µGal)	
					feet	meters			
G5N[1]	34°40′05″	118°08′26″	–4.774	7.3	2,441.606	744.2014	–4.770	1.0	+4
G3N	34°39′47″	118°08′20″	–4.684	9.0	2,459.698	749.7158	–4.659	9.3	+25
G2N	34°39′45″	118°08′20″	–4.633	1.5	2,461.429	750.2436	–4.606	2.6	+27
G1N	34°39′44″	118°08′20″	–4.611	4.5	2,462.123	750.4551	–4.580	2.6	+31
GR	34°40′05″	118°08′09″	–6.098	5.3	2,445.648	745.4336	–6.097	1.8	+1
G4W	34°39′43″	118°08′36″	–2.609	4.6	2,454.687	[2]748.1885	–2.577	6.5	+32
G3W	34°39′43″	118°08′28″	–3.648	4.3	2,459.406	749.6268	–3.610	5.0	+38
G2W	34°39′43″	118°08′25″	–4.014	4.5	2,460.469	749.9511	–3.980	2.1	+34
G1W	34°39′43″	118°08′24″	–4.196	1.4	2,461.487	750.2612	–4.162	7.5	+34
GZERO	34°39′43″	118°08′22″	–4.298	3.8	2,461.622	750.3025	–4.266	3.6	+32
G5S	34°39′32″	118°08′20″	–4.799	3.1	2,473.290	753.8587	–4.779	2.6	+20
G4S	34°39′35″	118°08′20″	–4.677	3.2	2,469.980	752.8501	–4.658	0.7	+19
G3S	34°39′39″	118°08′21″	–4.540	3.2	2,465.881	751.6004	–4.514	2.2	+26
G2S	34°39′41″	118°08′21″	–4.607	2.6	2,464.709	751.2433	–4.572	1.9	+35
G1S	34°39′42″	118°08′21″	–4.573	4.1	2,463.882	750.9911	–4.518	6.1	+55
G6E	34°39′44″	118°07′27″	–9.528	2.0	2,467.744	[2]752.1683	—	—	—
G4E	34°39′43″	118°08′16″	–5.250	1.3	2,465.964	751.6257	–5.237	1.9	+13
G3E	34°39′43″	118°08′19″	–4.927	3.5	2,464.277	751.1117	–4.906	2.1	+21
G2E	34°39′43″	118°08′20″	–4.753	7.6	2,463.550	750.8900	–4.716	6.0	+37
GNE	34°39′51″	118°08′07″	–6.086	6.4	2,460.296	[2]749.8981	—	—	—
				$\bar{x}$ = 4.2				$\bar{x}$ = 3.6	

See footnotes at end of table.

Table 3. Microgravity data collected during cycle 2 of the injection, storage, and recovery study at Lancaster, Antelope Valley, California, November 1996 through April 1997—Continued

Gravity station identifier (fig. 20)	Latitude	Longitude	Near completion of injection (April 5–12, 1997)				Change in microgravity from previous survey (μGal)	Change from initial survey	
			Mean change in microgravity (mGal)	Standard deviation (μGal)	Station altitude			Microgravity (μGal)	Station altitude (mm)
					feet	meters			
G5N	34°40′05″	118°08′26″	–4.767	4.3	2,441.614	744.2038	+3	+7	+2.4
G3N	34°39′47″	118°08′20″	–4.646	1.3	2,459.700	749.7166	+13	+38	+.8
G2N	34°39′45″	118°08′20″	–4.592	4.1	2,461.430	750.2440	+14	+41	+.4
G1N	34°39′44″	118°08′20″	–4.562	2.5	2462.124	750.4554	+18	+49	+.3
GR	34°40′05″	118°08′09″	–6.095	7.4	—	—	+2	+3	—
G4W	34°39′43″	118°08′36″	–2.572	3.5	—	—	+5	+37	—
G3W	34°39′44″	118°08′28″	–3.599	4.9	2,459.407	749.6272	+11	+49	+.4
G2W	34°39′43″	118°08′25″	–3.982	4.6	2,460.467	749.9504	-2	+32	–.7
G1W	34°39′43″	118°08′24″	–4.157	1.8	2,461.484	750.2602	+5	+39	–1.0
GZERO	34°39′43″	118°08′22″	–4.254	3.5	2,461.619	750.3014	+12	+44	–1.1
G5S	34°39′32″	118°08′20″	–4.769	3.1	—	—	+10	+30	—
G4S	34°39′35″	118°08′20″	–4.653	4.8	2,469.983	752.8509	+5	+24	+.8
G3S	34°39′39″	118°08′21″	–4.510	2.5	2,465.879	751.6000	+4	+30	–.4
G2S	34°39′41″	118°08′21″	–4.563	4.7	2,464.708	751.2431	+9	+44	–.2
G1S	34°39′42″	118°08′21″	–4.507	2.5	2,463.881	750.9908	+11	+66	–.3
G6E	34°39′44″	118°07′27″	–9.519	1.4	—	—	—	+9	—
G4E	34°39′43″	118°08′16″	–5.218	1.9	2,465.966	751.6265	+19	+32	–.8
G3E	34°39′43″	118°08′19″	–4.887	0.6	2,464.279	751.1123	+19	+40	–.6
G2E	34°39′43″	118°08′20″	–4.715	5.0	2,463.550	750.8901	+1	+38	+.1
GNE	34°39′51″	118°08′07″	–6.077	3.8	—	—	—	+9	—
				$\bar{x} = 3.4$					
QTZ[3]	34°38′43″	118°12′01″	—	—	2,638.7	[4]804.3	—	—	—

[1] Altitude measured at bench mark G5aN, located on same concrete pad as gravity station G5N, but outside of extensometer building.
[2] Altitude measured during March 26–28, 1996.
[3] Bedrock promontory used as a stable gravity reference.
[4] Determined by GPS in 1996.

Table 4. Microgravity data collected during cycle 3 of the injection, storage, and recovery study at Lancaster, Antelope Valley, California, February 1998 and June 1998

[Latitude and longitude are referenced to the North American Datum of 1983 (NAD83) determined using GPS in 1996–97. Gravity measured relative to Quartz Hill bedrock reference station 3.6 miles from injection site (fig. 3). Station altitudes are referenced to the National Geodetic Vertical Datum of 1929 (NGVD29) and were measured by leveling to second-order standards of accuracy. Altitudes for the pre-injection survey were measured on February 17, 1998. mGal, milliGal; µGal, microGal. $\bar{x}$, mean. —, no data]

Gravity station identifier (fig. 20)	Latitude	Longitude	Pre-injection survey (February 18–25, 1998)				Near-completion of injection (June 6–12, 1998)		Change in microgravity from previous survey (µGal)
			Mean change in microgravity (mGal)	Standard deviation (µGal)	Station altitude		Mean change in microgravity (mGal)	Standard deviation (µGal)	
					feet	meters			
G8N	34°39′57″	118°08′20″	–4.952	0.4	2,450.716	746.9783	–4.954	5.0	–2
G5N	34°40′05″	118°08′26″	–4.799	3.9	2,441.609	744.2025	–4.801	.9	–2
G4N	34°39′50″	118°08′20″	–4.772	1.9	2,456.870	748.8540	–4.766	2.4	+6
G3N	34°39′47″	118°08′20″	–4.688	1.0	2,459.696	749.7153	–4.681	1.6	+7
G2N	34°39′45″	118°08′20″	–4.645	3.5	2,461.425	750.2424	–4.626	1.2	+19
G1N	34°39′44″	118°08′20″	–4.648	1.9	2,462.119	750.4539	–4.608	3.3	+40
GR	34°40′05″	118°08′09″	–6.104	1.0	—	—	–6.106	3.9	–2
G5W	34°39′43″	118°08′43″	–1.831	1.7	2,453.583	747.8520	–1.802	2.5	+29
G4W	34°39′43″	118°08′36″	–2.559	2.1	2,454.684	748.1876	–2.546	4.0	+13
G3W	34°39′43″	118°08′28″	–3.666	.9	2,459.401	749.6255	–3.629	.7	+37
G2W	34°39′43″	118°08′25″	–4.022	3.1	2,460.472	749.9519	–4.012	4.0	+10
G1W	34°39′43″	118°08′24″	–4.193	1.9	2,461.484	750.2603	–4.179	3.2	+14
GZERO	34°39′43″	118°08′22″	–4.284	1.2	2,461.617	750.3009	–4.263	8.9	+21
G6S	34°39′22″	118°08′20″	–5.322	1.8	2,484.130	757.1629	–5.315	4.8	+7
G4S	34°39′35″	118°08′20″	–4.697	2.0	2,469.956	752.8427	–4.662	4.4	+35
G3S	34°39′39″	118°08′21″	–4.546	2.5	2,465.851	751.5914	–4.532	2.3	+14
G2S	34°39′41″	118°08′21″	–4.610	2.4	2,464.684	751.2356	–4.583	3.6	+27
G1S	34°39′42″	118°08′21″	–4.562	3.8	2,463.866	750.9865	–4.536	5.7	+26
G5E	34°39′43″	118°08′13″	–5.686	1.7	2,467.990	752.2432	–5.658	0.4	+28
G4E	34°39′43″	118°08′16″	–5.276	2.1	2,465.942	751.6191	–5.235	1.0	+41
G3E	34°39′43″	118°08′19″	–4.984	2.1	2,464.275	751.1109	–4.957	1.8	+27
G2E	34°39′43″	118°08′20″	–4.826	2.4	2,463.547	750.8891	–4.809	5.5	+17
G1E	34°39′43″	118°08′21″	–4.563	2.4	2,462.418	750.5450	–4.521	4.9	+42
GNE	34°39′51″	118°08′07″	–6.096	1.3	—	—	–6.090	.2	+6
NW5	34°39′57″	118°08′33″	–3.645	1.1	2,444.944	745.2189	–3.628	1.6	+17
NW4	34°39′57″	118°08′34″	–3.487	1.0	2,444.379	745.0467	–3.475	3.7	+12
NW2	34°39′56″	118°08′35″	–3.318	1.7	2,445.158	745.2841	–3.311	1.6	+7
GSE	34°39′30″	118°08′10″	–6.551	3.9	2,481.580	756.3855	–6.505	4.2	+46
GSW	34°39′32″	118°08′29″	–3.726	.7	2,471.664	753.3632	–3.706	12.2	+20
Boat	34°39′25″	118°08′02″	–7.707	1.5	2,489.602	758.8308	–7.679	3.2	+28
Josh	34°39′43″	118°08′05″	–6.383	2.8	2,468.732	752.4696	–6.356	10.4	+27
				$\bar{x}$ = 2.0				$\bar{x}$ = 3.6	

GEODETIC MONITORING

Three geodetic monitoring techniques were used to measure the geographical distribution of land-surface deformation during the injection phase of each cycle: differential leveling of a network of vertical-control bench marks to measure land-surface altitude changes; continuous GPS surveying to monitor land-surface altitude changes at the injection site; and tiltmeter monitoring to measure land-surface inclination changes near the injection site.

Differential-Leveling Network

A differential-leveling network consisting of 124 vertical-control bench marks was installed in September 1995 to monitor land-surface altitude changes near the injection site (fig. 23). The bench marks were spaced about 130 ft apart along four lines radiating in each cardinal direction from near the intersection of Avenue L and 5th Street West. The south and north lines, parallel to 5th Street West, were about 1 mi long. The south line ended about 0.25 mi north of Avenue M and the north line ended at Avenue K. The west and east lines, parallel to Avenue L, were about 0.5 mi long. The west line ended at 10th Street West, but three additional bench marks were installed between 10th Street West and 20th Street West. The east line ended at Sierra Highway, but two additional bench marks were installed between Sierra Highway and 5th Street East. Seven bench marks were installed near the injection wells along a second west-east line which was about 900 ft long. Three bench marks were installed between 5th Street West and the extensometer building. One bench mark was installed inside the extensometer building.

Bench-Mark Installation

Bench marks were installed on steel rods or rebar, in concrete, or on other materials (table 5). Most of the bench marks were installed in 3-foot-deep holes encased by 3-foot lengths of 6-inch-diameter PVC casing to keep the soil from contacting the bench-mark rod. Bench marks installed in 3-foot-deep holes consisted of two 4-foot-long sections of 0.625-inch-diameter copper-plated steel rod or rebar. The rods and rebar were pounded into the soil with a hydraulic hammer. A 3.25-inch-diameter brass tablet, stamped with the bench-mark identifier, was cemented to the top of the rods and rebar with industrial-grade epoxy (fig. 24). Either brass tablets, stamped with the bench-mark identifier, or steel bolts, mounted in concrete, were used for some of the bench marks. Locations where bench marks were installed in concrete surfaces include sidewalks along Avenue L, the well pad at 7N/12W-27P3, and the extensometer building pad. Other bench marks used were a Los Angeles County bench mark and a metal sewer cover.

LACDPW personnel conducted a series of seven GPS surveying sessions (table 6) on October 23 and 24, 1995, to determine the latitude, longitude, and altitude of each bench mark. The GPS surveys were done relative to existing bench marks (regional control points) with known coordinates. Five bench marks (F1147, 104-7, OBAN, SAHARA, and MARGO) measured in 1992 by the USGS and LACDPW were used as regional control points (fig. 25). The first survey was a 6-hour static session during which five new bench marks (ZERO, N35, S35, E20, and W21) were surveyed simultaneously with the two regional control points (F1147 and 104-7) to establish the five new bench marks as local control points near the injection site. In the second survey, the same set of seven bench marks was observed during a 2-hour static session to confirm the results of the first survey. The third, fourth, and fifth surveys were fast static sessions during which base receivers were operated at OBAN, SAHARA, W23, or MARGO and the local control points were observed for a period of about 10 minutes. These surveys were done to provide an independent check of the coordinates for the two regional control points (F1147 and 104-7) and the local control points. The sixth and seventh surveys were fast static sessions during which base receivers were operated at one or more of the local control points and the remaining bench marks were observed for a period of about 10 minutes.

The GPS-measured horizontal coordinates for each bench mark were converted to latitude and longitude determined relative to the North American Datum of 1983 (NAD83). NAD83 is the satellite reference system that most closely approximates the Earth's shape in the Antelope Valley (Ikehara and Phillips, 1994). The GPS-measured vertical coordinate for each bench mark (ellipsoidal height) and the GPS-derived altitude (orthometric height) were used to determine land-surface altitude. The ellipsoid height is the vertical coordinate relative to the satellite reference system, NAD83. Orthometric heights were determined using the GEOID93 model and land-surface altitudes from the 1992 GPS survey (Ikehara and Phillips, 1994). Land-surface altitudes from the 1992 GPS survey were

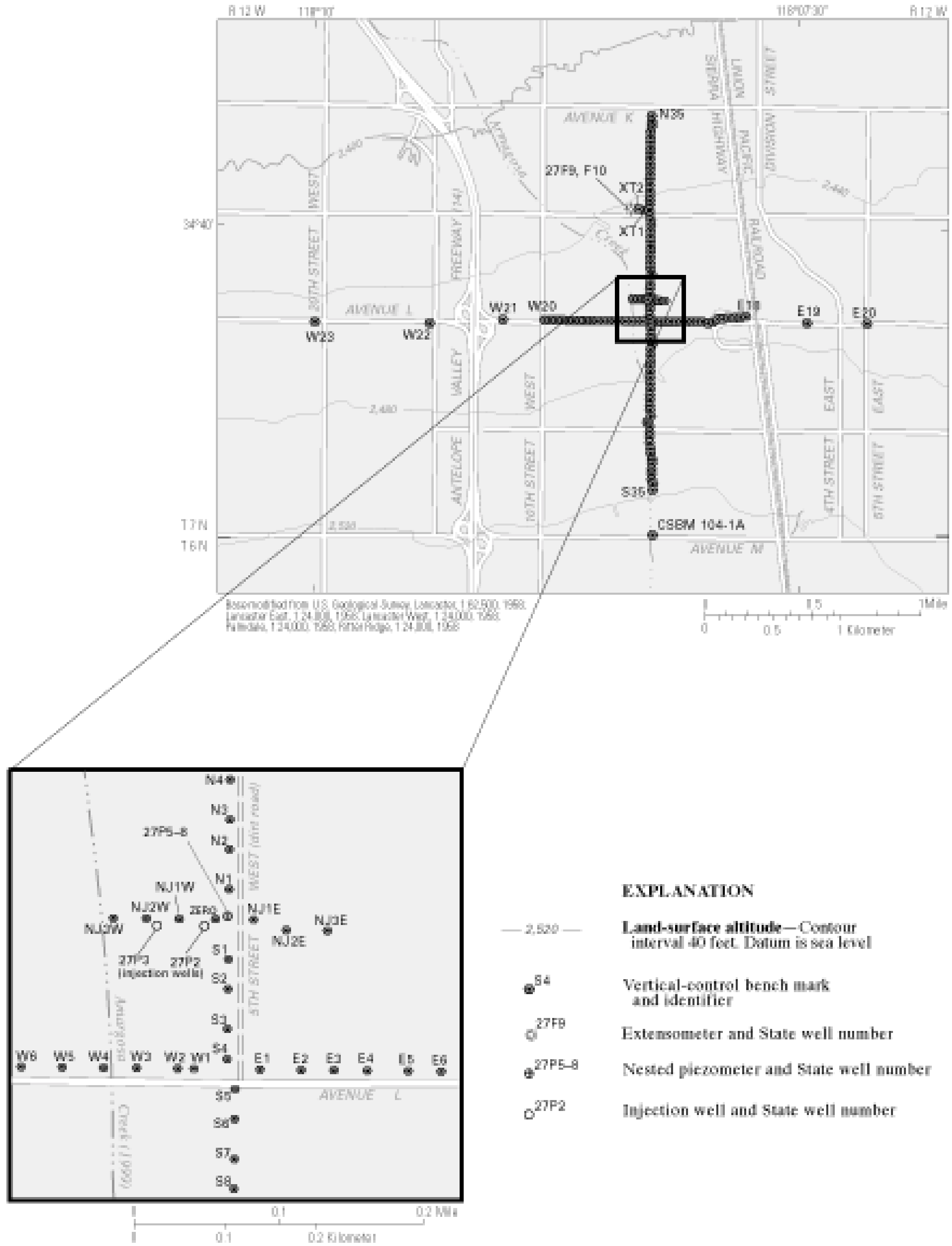

Figure 23. Locations of vertical-control bench marks used in differential-leveling surveys for the injection, storage, and recovery study at Lancaster, Antelope Valley, California.

based on the National Geodetic Vertical Datum of 1929 (NGVD29).

Differential-Leveling Surveys

Several differential-leveling surveys were done by USGS and LACDPW personnel during various phases of the injection, storage, and recovery study (table 7). For cycle 1, surveys were done during the pre-injection phase and during the initial and midway parts of the injection phase. For cycle 2, surveys were done during the pre-injection phase, during the initial part of the injection phase, and at the end of the injection phase. A final survey was done during the pre-injection phase for cycle 3.

During all the surveys, almost every bench mark within about 800 ft of the injection wells was surveyed because the greatest land-surface altitude changes were expected to occur closest to the injection wells. Most of the bench marks in the network were surveyed at least once during cycles 1 and 2. Some of the gravity stations established for this study also were surveyed to ensure that observed changes in gravity were due to changes in aquifer mass and not by changes in station altitude owing to aquifer-system deformation (see “Microgravity Surveys” section).

USGS personnel conducted differential leveling of the bench-mark network on September 25 and 26, 1995, using a Wild NA2 instrument and graduated-scale level rods. On September 27 and 28, 1995, LACDPW personnel leveled the bench-mark network using a Wild NA3000 instrument and Invar bar-code rods. The bar-code rods produced results comparable with the conventional graduated-scale rods and thus were used for all subsequent surveys. All the surveys were done to first-order accuracy using second-order methods (Federal Geodetic Control Committee, 1984).

The initial differential-leveling surveys done in late September 1995 began at a previously established bench mark with a known land-surface altitude. The

Table 5. Summary of materials used to construct bench marks for the injection, storage, and recovery study at Lancaster, Antelope Valley, California, September 1995 through September 1998

[Bench-mark locations (except where footnoted) shown in figure 23. Because of the constraints of the figure size, only the bench marks within about 800 feet of the injection wells are labeled on the figure—almost all the bench marks in this vicinity were surveyed because the greatest land-surface altitude changes were expected to occur closest to the injection wells]

Bench-mark name	Material	Number of bench marks
Surveying line: south		
S1–S4, S6–S8, S10–S14, S16–S18	Rod	15
S19A, S19B, S20–S35	Rebar	18
S9	Concrete	1
[1]S5, [2]S15	Other	2
Surveying line: north		
N1–N19	Rod	19
N20–N35	Rebar	13
Surveying line: west		
W1, W10, W12, W13	Rod	4
W21–W23	Rebar	3
W2–W9, W11, W14–W20	Concrete	16
Surveying line: east		
E1–E9, E14, E15	Rod	11
E10–E13, E16–E20	Concrete	9
Surveying line: short west and east		
NJ1E–NJ3E, NJ1W, NJ3W	Rebar	5
NJ2W	Concrete	1
Extensometer		
XT2	Rebar	1
[3]G5aN, XT1	Concrete	2
Injection site		
ZERO	Rod	1
Total		124

[1] Metal Los Angeles County bench mark.
[2] Metal sewer cover.
[3] Bolt set in concrete of extensometer building pad adjacent to G5N. See figure 20.

Figure 24. Typical vertical-control bench mark used for differential-leveling surveys.

altitude of the bench mark [Los Angeles County Surveyor Bench Mark (CSBM) 104-1A, also known as DL 3197] was designated the starting altitude for computing land-surface altitudes of the new bench marks established for this study. CSBM 104-1A is located on Avenue M, about 0.2 mi south of bench mark S35 (fig. 23). CSBM 104-1A was installed in 1967 and was most recently leveled and adjusted in 1991 as part of the Los Angeles County Baseline leveling. The published altitude is 2,531.264 ft (County of Los Angeles, 1991). This bench mark was measured during several leveling surveys between 1967 and 1991, and results of the surveys indicate that there was no change in land-surface altitude at this bench mark during this period. Results of previous land-subsidence studies, however, have shown that notable land subsidence was occurring north of CSBM 104-1A where the sedimentary deposits gradually become more fine-grained (Ikehara and Phillips, 1994).

Data Processing

Differential-leveling surveys were done to measure the difference in altitude between two bench marks. The altitude of each bench mark was computed by adding or subtracting the measured difference in altitude to or from the altitude of the previous bench mark in the surveying line. The altitudes of the bench marks on the south-north line were computed relative to the altitude of bench mark CSBM 104-1A for about half of the surveys. For surveys that did not extend to CSBM 104-1A, the altitudes on the south-north line were computed relative to the altitude of the southernmost bench mark computed for the previous survey. The altitudes of the bench marks on the west-east line were computed relative to the altitude of bench mark S4, where the west-east line intersects the south-north line. Altitudes of bench marks on the short west-east line near the injection site were computed relative to the altitude of bench mark ZERO. Land-surface altitudes from all differential-leveling surveys are shown in figures 26–29.

Continuous GPS Surveying

A permanent, continuous GPS station was established at the injection site to monitor land-surface altitude changes. Continuous GPS surveying provided a practical alternative to labor-intensive daily or subdaily (every 3 or 6 hours) differential-leveling surveying. Continuous GPS surveying also measured short-term land-surface altitude changes that could not be measured with periodic differential-leveling surveying.

Table 6. Summary of Global Positioning System (GPS) surveying sessions used to determine coordinates for bench marks in the differential-leveling network for the injection, storage, and recovery study at Lancaster, Antelope Valley, California, October 23 and 24, 1995

[USGS, U.S. Geological Survey]

GPS session	Observation session type	Bench marks used as control points for 6- and 2-hour static sessions and as base receivers for fast static sessions	Bench marks used as unknown points for 6- and 2-hour static points and for fast static rover points	Notes
1	6-hour static	F1147, 104-7 (DL 1373)[1]	ZERO, N35, S35, E20, W21	Control points for this session were also used in 1992 GPS survey (USGS)
2	2-hour static	F1147, 104-7 (DL 1373)[1]	ZERO, N35, S35, E20, W21	Duplicate survey to check repeatability
3	Fast static	OBAN, SAHARA	F1147, 104-7 (DL 1373)[1], N35, S35, E20, W21	Independent check on horizontal control
4	Fast static	W23	F1147, 104-7 (DL 1373)[1], N35, S35, E20, W21	Coordinates for bench mark W23 are unknown
5	Fast static	MARGO	ZERO, N35, S35, E20, W21	Independent check on horizontal control
6	Fast static	ZERO, N35, S35, E20, W21	NJ3E, NJ3W, well 7N/12W-27F3 (4-44)[1], XT2, DE2, W22, W23	Points used in session 6 are in the study area, but not necessarily on a network leg
7	Fast static	ZERO	N1–35, S1–35, E1–20, W1–21, NJ1E–3E, NJ1W–3W	Four primary legs of network and two secondary legs near injection wells

[1] Local identifier

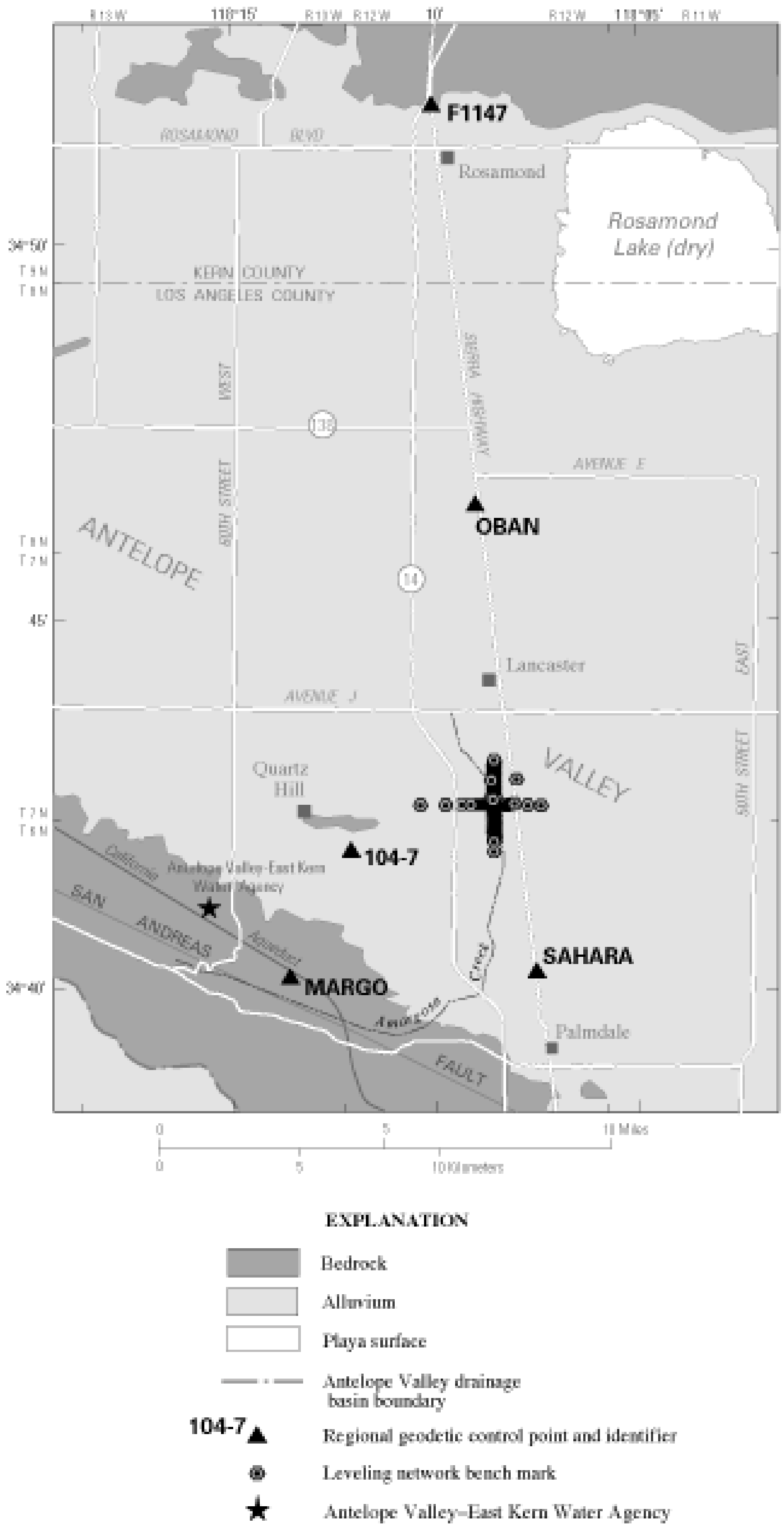

Figure 25. Locations of regional geodetic control points used to determine horizontal and vertical coordinates for bench marks in the differential-leveling network for the injection, storage, and recovery study at Lancaster, Antelope Valley, California.

GPS Station Construction and Instrumentation

An antenna mount for the permanent, continuous GPS station (fig. 30*A*) was constructed in March 1996 about 60 ft east-northeast of injection well 7N/12W-27P2 (fig. 3). The 8-foot-high antenna mount was erected by cementing a 2-inch-diameter steel pipe into the ground. The top of the pipe was braced by four legs of 1.5-inch steel welded to vertical supports projected about 2 ft above land surface. The GPS antenna was secured to the top of the pipe with a reducing fitting and threaded bolt. The GPS receiver, telephone modem, and backup batteries were housed in a nearby enclosure (fig. 30*B*).

A Trimble 4000SSE dual-frequency (P-code) receiver and a microstrip L1/L2 antenna with a ground plane were used during cycle 1. An Ashtech LD-XII receiver was used during cycle 2; and an Ashtech Z-XII receiver and a Dorne Margolin choke-ring antenna, contributed by the Southern California Integrated GPS Network (SCIGN), were used during cycle 3. The continuous GPS station was incorporated into the SCIGN network under the station name LINJ (Lancaster INJection well) before cycle 3 started.

A temporary continuous GPS station was set up as a base station during cycle 2 because of changes in data collection and processing procedures. The temporary station was 6.43 mi west-southwest of the injection site in the parking lot of the AVEK district office (fig. 1). This location was selected for the temporary base station because it is on bedrock and was considered vertically stable, and because of its proximity to the permanent GPS station. The temporary GPS station also was equipped with an Ashtech LD-XII receiver and a microstrip L1/L2 antenna. A wooden tripod was used to mount the antenna approximately 5 ft above land surface. The GPS receiver and a car battery were stored in a waterproof container adjacent to the tripod (fig. 31).

Data Collection and Processing

Continuous GPS data were collected at least 7 days prior to the start of the injection phase of each cycle to determine baseline conditions. GPS data were collected only for the initial period of injection during cycles 1 and 2 because it was expected that land-surface altitude changes would occur as a ground-water mound formed during injection. Because the permanent, continuous GPS station became a part of the SCIGN network before the start of cycle 3, it was possible to collect GPS data for all three phases of that cycle. Data were recorded at intervals of either 30 or 120 seconds and compiled into sessions representing 3-, 6-, or 24-hour sessions for various survey periods (table 8). Data were downloaded by modem once a day for cycles 1 and 3 and by laptop computer every 1 to 3 weeks for cycle 2.

GPS data collected during cycles 1 and 3 were processed by computing the daily or subdaily (every 3 or 6 hours) position (latitude, longitude, and land-surface altitude) of the permanent GPS station at the injection site in relation to the known positions of other GPS stations in the SCIGN network (Nancy King, U.S. Geological Survey, written commun., 2000). GPS data collected during cycle 2 were processed by computing the ellipsoid height for the permanent GPS station at the injection site relative to a fixed ellipsoid height for the temporary GPS base station at the AVEK district office parking lot.

Daily solutions, representing the mean land-surface altitude for each 24-hour period, were computed for cycles 1 and 3 using the 24-hour data files from the injection site and three SCIGN stations (Nancy King, U.S. Geological Survey, written commun., 2000). Daily solutions for cycle 2 were computed as the mean land-surface altitude for the 3-hour and 6-hour subdaily data files. Daily solutions are shown in figure 32 as the change in land-surface altitude relative to an initial starting value of zero for the following dates: April 7 to April 13, 1996 (cycle 1); November 6 to December 4, 1996 (cycle 2); April 9 to May 9, 1998 (cycle 3).

Table 7. Survey periods of differential-leveling surveys for the injection, storage, and recovery study at Lancaster, Antelope Valley, California, September 1995 through February 1998

Phase	Survey period		
	Injection cycle 1	Injection cycle 2	Injection cycle 3
Pre-injection	September 25–28, 1995 March 26–27, 1996	November 4, 1996	February 17, 1998
Injection, initial	April 15–16, 1996	November 12–15, 1996	
Injection, midway	April 29, 1996		
Injection, end		April 9, 1997	

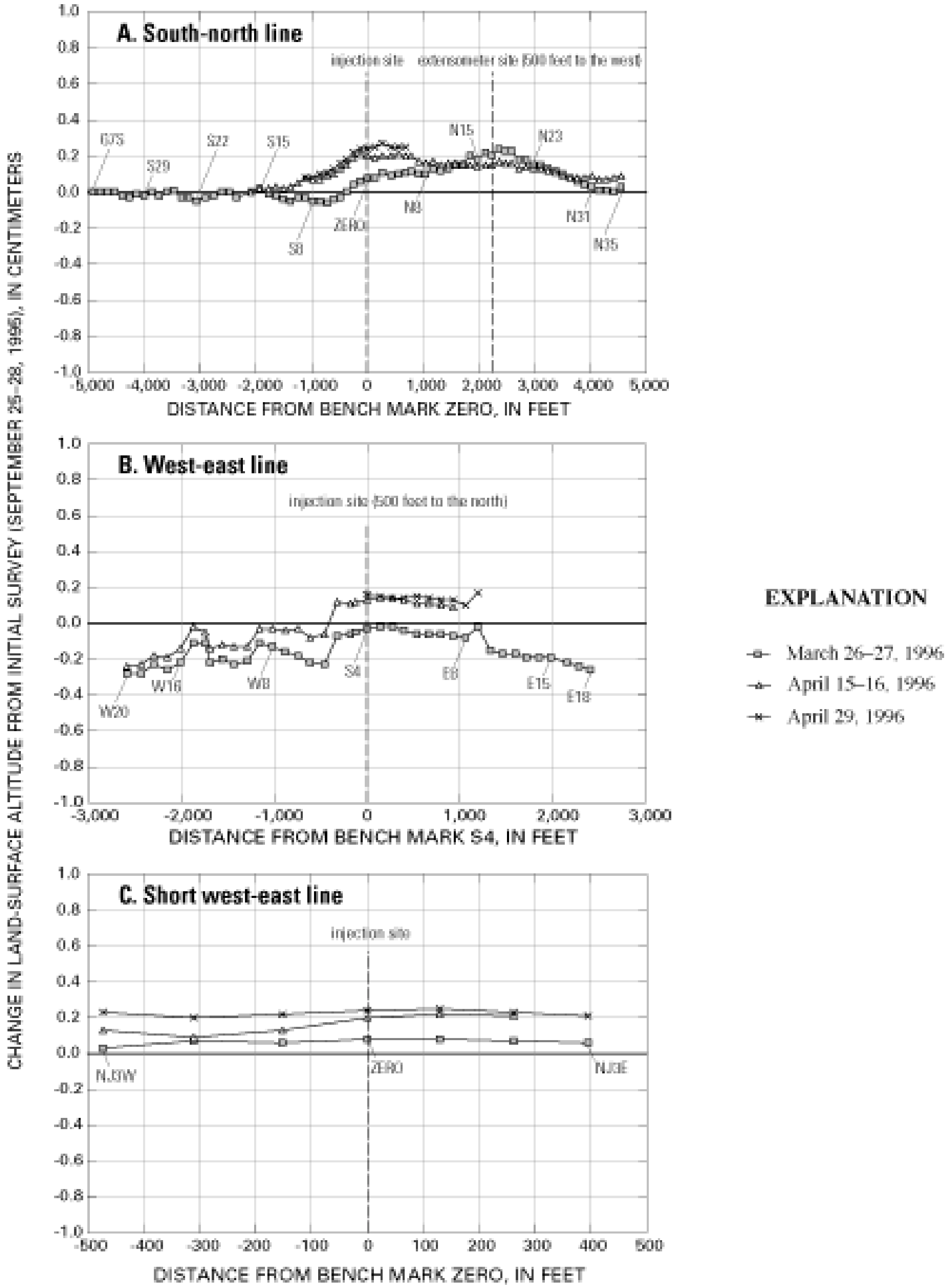

Figure 26. Change in land-surface altitude of bench marks and gravity stations measured during surveys on March 26—27, April 15—16, and April 29, 1996, relative to land-surface altitudes measured on September 25—28, 1995, in Lancaster, Antelope Valley, California. (Gravity stations are denoted by a "G" as the first character of the station identifier.)

Subdaily solutions were computed to determine whether changes in land-surface altitude occurred over periods of less than 24 hours (fig. 33). The subdaily solutions represent the average land-surface altitude for 4-hour periods for cycle 1 and for 3- or 6-hour periods for cycle 2. The same dates used for the daily solutions for cycles 1 and 2 were used for the subdaily solutions for cycles 1 and 2 (figs. 32 and 33, respectively). For cycle 1, the subdaily solutions were computed by reprocessing the 24-hour sessions as six 4-hour sessions (Nancy King, U.S. Geological Survey, written commun., 2000). For cycle 2, the subdaily solutions were computed by dividing each 24-hour data session into either four 6-hour periods or eight 3-hour periods depending on the number of recorded data sessions (table 8). The subdaily solutions are shown in figure 33 as the change in land-surface altitude relative to an initial starting value of zero. Several of the subdaily solutions for cycle 1 are not shown because of erroneous data.

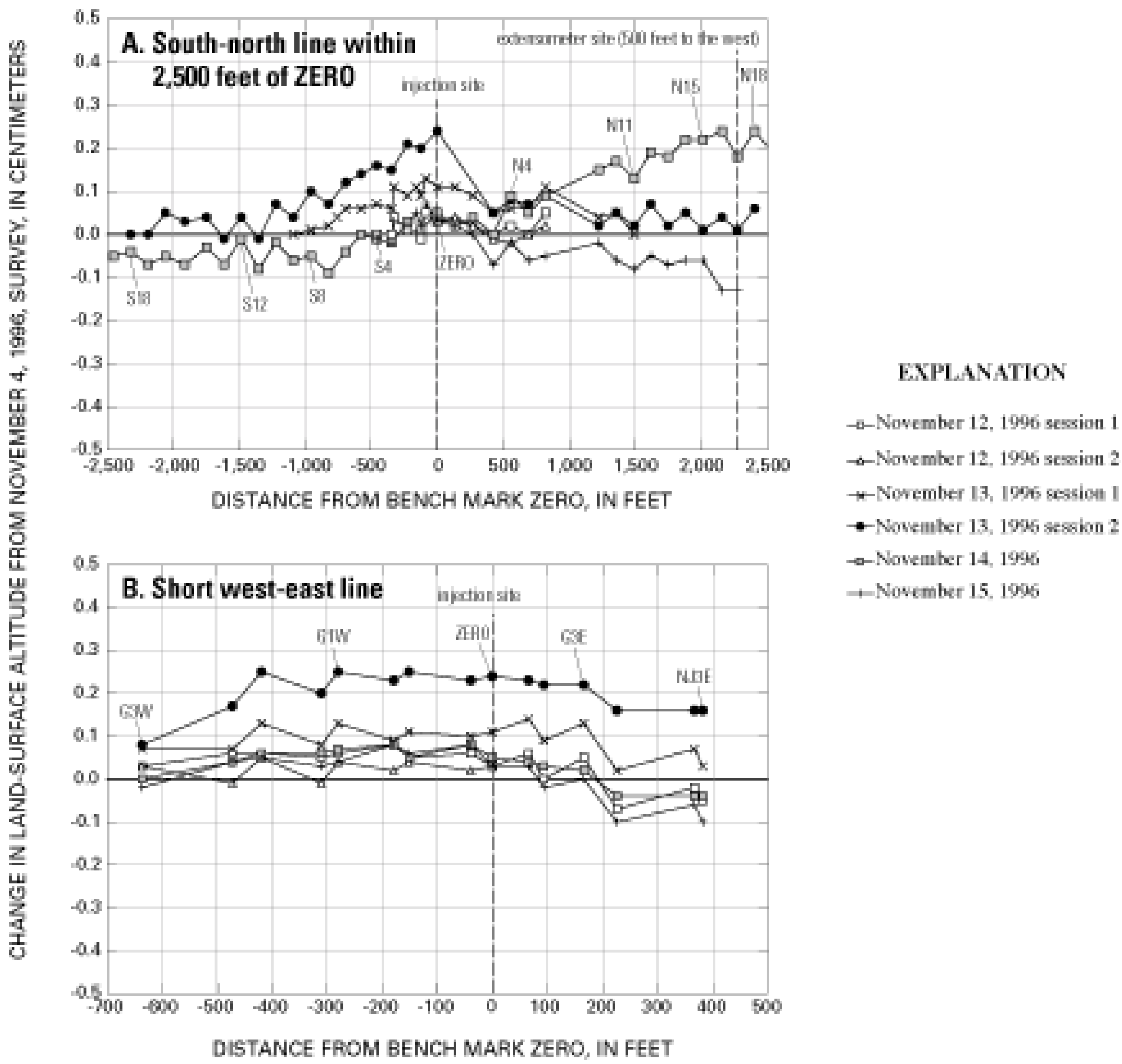

Figure 27. Change in land-surface altitude of bench marks and gravity stations measured during surveys on November 12—15, 1996, relative to land-surface altitudes measured on November 4, 1996, in Lancaster, Antelope Valley, California. (Gravity stations are denoted by a "G" as the first character of the station identifier.)

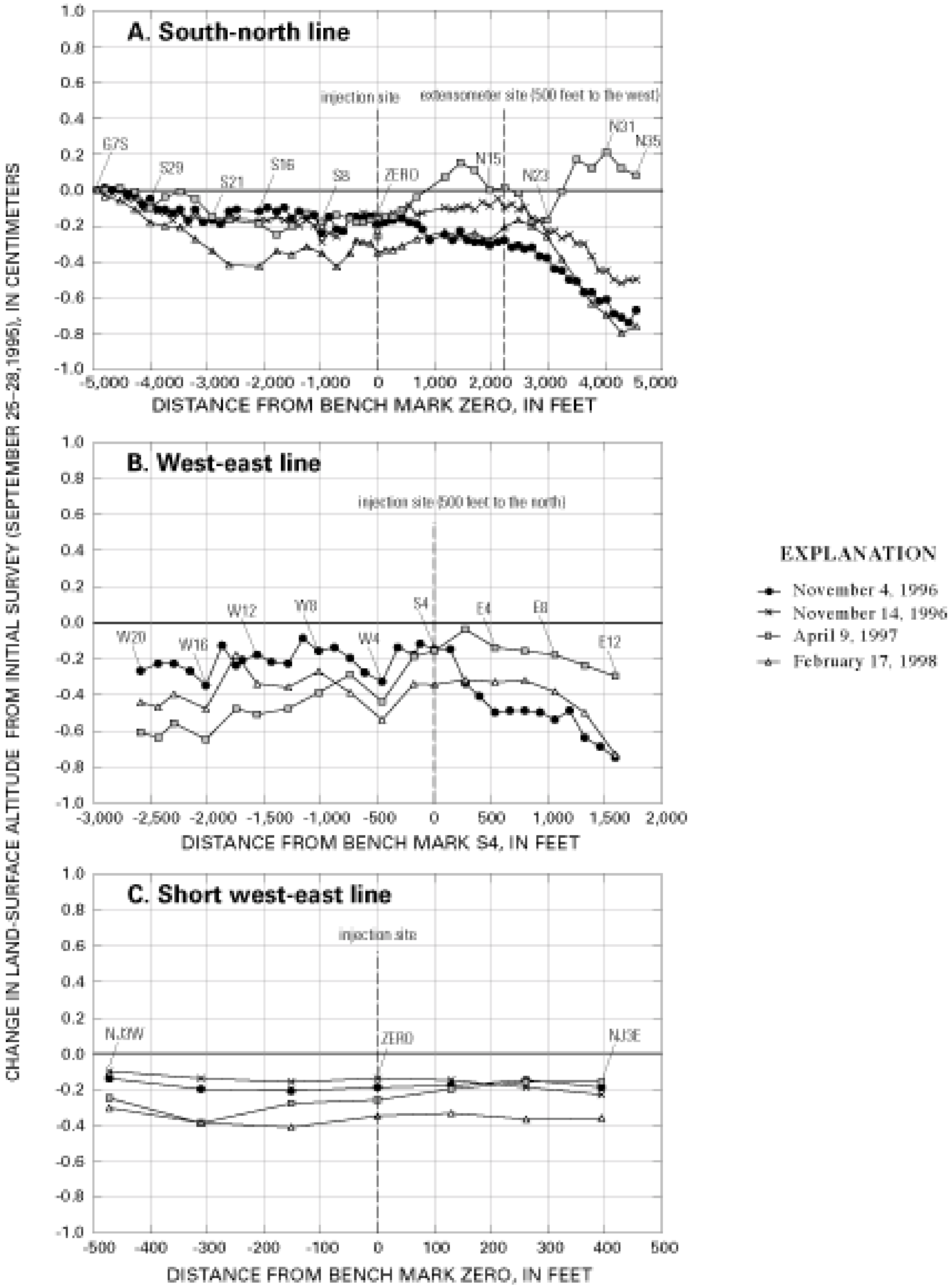

Figure 28. Change in land-surface altitude of bench marks and gravity stations measured during surveys on November 4, 1996; November 14, 1996; April 9, 1997; and February 17, 1998, relative to land-surface altitudes measured on September 25—28, 1995, in Lancaster, Antelope Valley, California. (Gravity stations are denoted by a “G” as the first character of the station identifier.)

Tiltmeter Network

A network of biaxial platform tiltmeters (Applied Geomechanics Model 701) was installed near the injection site to monitor the magnitude and direction of ground tilting (Robert Larson, Los Angeles County Department of Public Works, written commun., 1997). Tiltmeters can simultaneously monitor tilt in two directions (north-south and east-west). The resolution of the Model 701 tiltmeters is 0.1 microradian (a microradian is equivalent to 0.000057 degree). Personnel from the LACDPW, Materials Engineering Division, installed and operated the tiltmeters and processed all recorded data.

Installation

Tiltmeters were used to monitor tilt associated with direct well injection during cycle 2. Six tiltmeters were installed in an L-shaped configuration aligned west and north of injection well 7N/12W-27P3 (fig. 34). The three tiltmeters in the western array were positioned at distances of 90, 198, and 755 ft from well 7N/12W-27P3 and identified as sites 1W, 2W, and 3W, respectively. The three tiltmeters in the northern array were positioned at distances of 134, 305, and 1,323 ft from well 7N/12W-27P3 and identified as sites 1N, 2N, and 3N, respectively.

The tiltmeters were installed 18 inches below land surface in a 2-foot-square (ft^2) lockable, bottomless metal vaults buried in the ground (fig. 35). Each tiltmeter was placed on a concrete block (6 × 6 × 2 inches) embedded in approximately 6 inches of #2-12 filter sand (Robert Larson, Los Angeles County Department of Public Works, written commun., 1997). The sand was placed on ground that had been foot tamped and was used to prevent soil moisture from contacting the instrumentation. A data logger and a 12-volt (V) car battery were installed in the second vault of each array. Cables connecting the battery and the data logger to the tiltmeters were buried under 6 inches of soil to reduce the likelihood of disturbance. Each tiltmeter was set to the high-gain mode (which can measure as much as a 0.5 degree tilt) with the filter on.

Data Collection and Processing

Tiltmeter readings were recorded (in millivolts) on the data logger at 10-minute intervals. Data from each retrieval were combined into a data file that consisted of 12,068 readings. Signal spikes greater than 10 millivolts were deleted. Data were averaged for 6-hour intervals and were converted from millivolts to

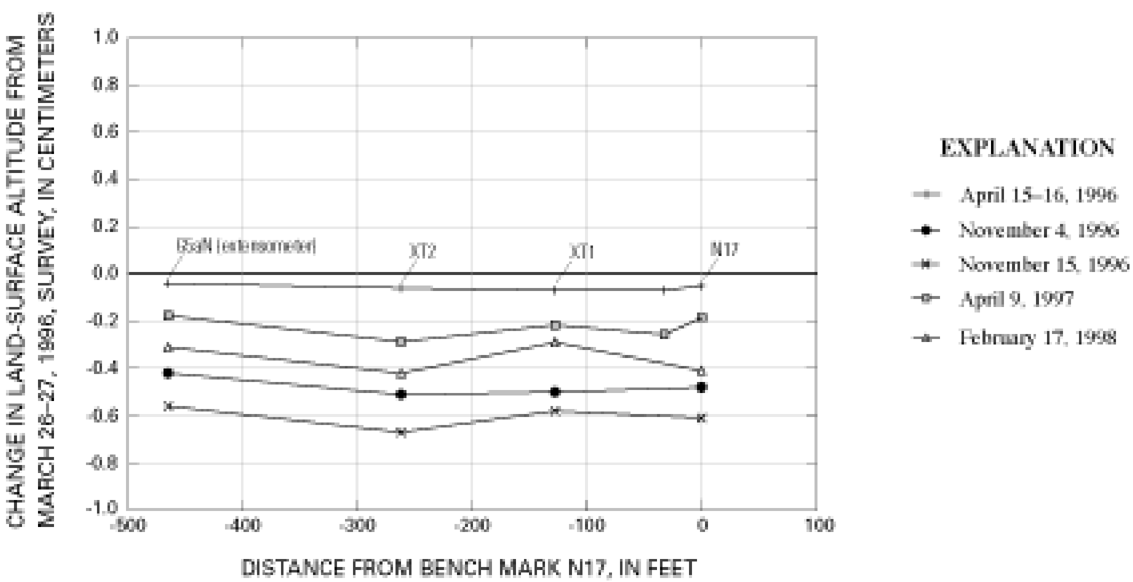

Figure 29. Change in land-surface altitude of bench marks along the extensometer line of the differential-leveling network measured during surveys on April 15–16, 1996; November 4, 1996; November 15, 1996; April 9, 1997; and February 17, 1998, relative to land-surface altitudes measured on March 26–27, 1996, in Lancaster, Antelope Valley, California. (Gravity stations are denoted by a "G" as the first character of the station identifier. G5aN is a bench mark adjacent to the extensometer.)

A.

B.

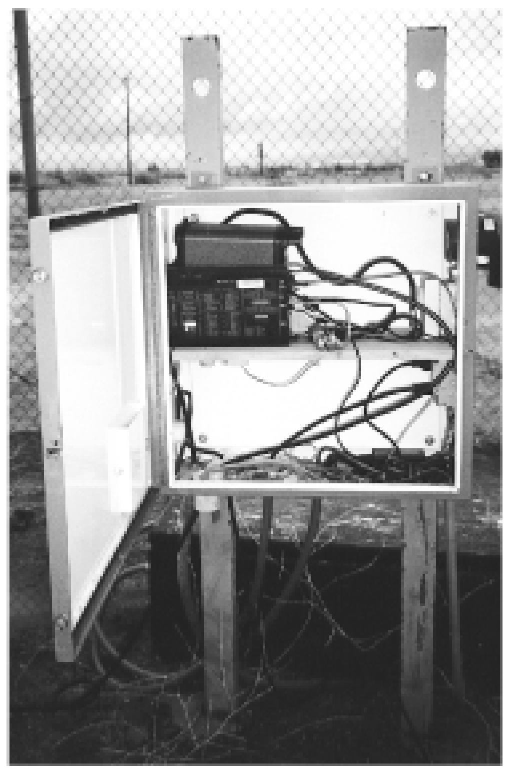

Figure 30. Permanent Global Positioning System (GPS) station at the injection site in Lancaster, Antelope Valley, California. ***A***, Antenna (photographed in September 1998). ***B***, Receiver with modem.

Figure 31. Temporary Global Positioning System (GPS) base station at the Antelope Valley–East Kern (AVEK) Water Agency district office in Antelope Valley, California.

Table 8. Survey periods of continuous Global Positioning System (GPS) surveys, data recording intervals, and number and duration of daily data sessions for the injection, storage, and recovery study at Lancaster, Antelope Valley, California, March 1996 through September 1998

Injection cycle	Survey period	Data recording interval, in seconds	Number of data sessions per day and session duration
1	March 26, 1996–April 15, 1996	30	one 24-hour
2	November 5, 1996–November 12, 1996	30	four 6-hour
	November 12, 1996–December 23, 1996	30	eight 3-hour
	December 23, 1996–December 31, 1996	120	four 6-hour
	January 9, 1997–January 30, 1997	120	four 6-hour
3	February 3, 1998–September 30, 1998	30	one 24-hour

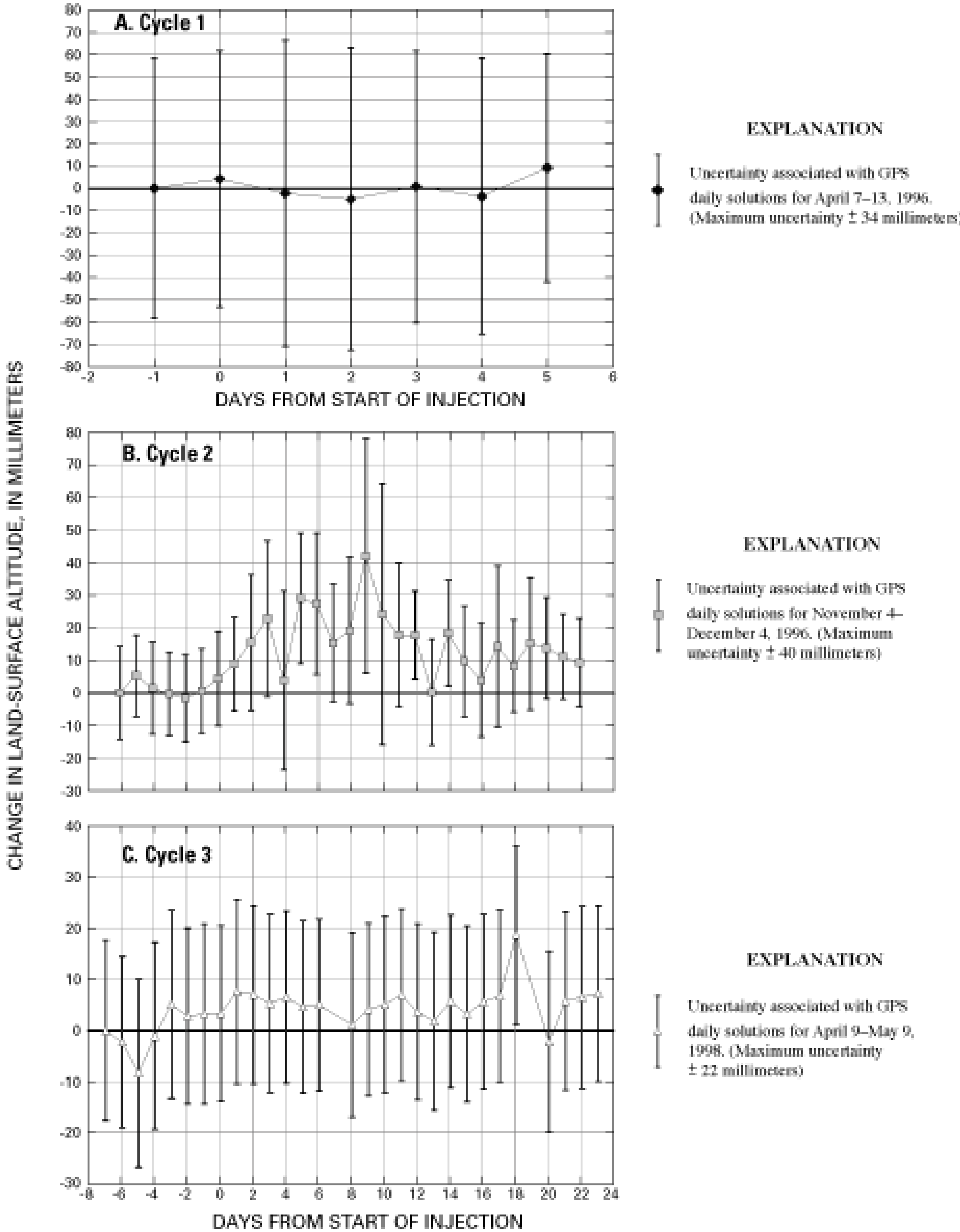

Figure 32. Change in land-surface altitude at the injection site derived from continuous Global Positioning System (GPS) daily solutions for the injection phases of cycles 1, 2, and 3 at Lancaster, Antelope Valley, California. (The uncertainty associated with each graph corresponds to two standard deviations and a confidence interval of 95 percent.)

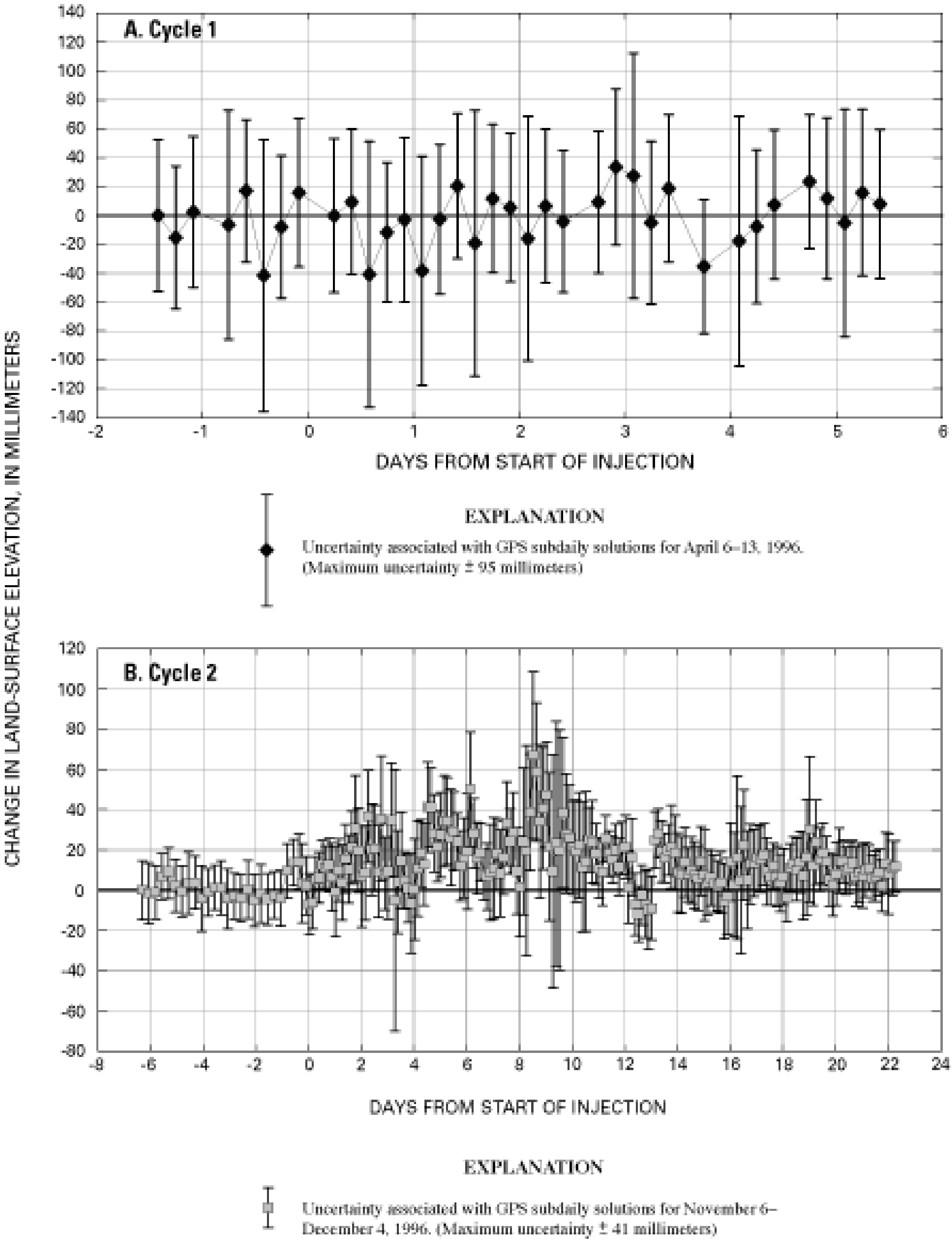

Figure 33. Change in land-surface altitude at the injection site derived from continuous Global Positioning System (GPS) subdaily solutions for the injection phases of cycles 1 and 2 at Lancaster, Antelope Valley, California. (The uncertainty associated with each graph corresponds to two standard deviations and a confidence interval of 95 percent.)

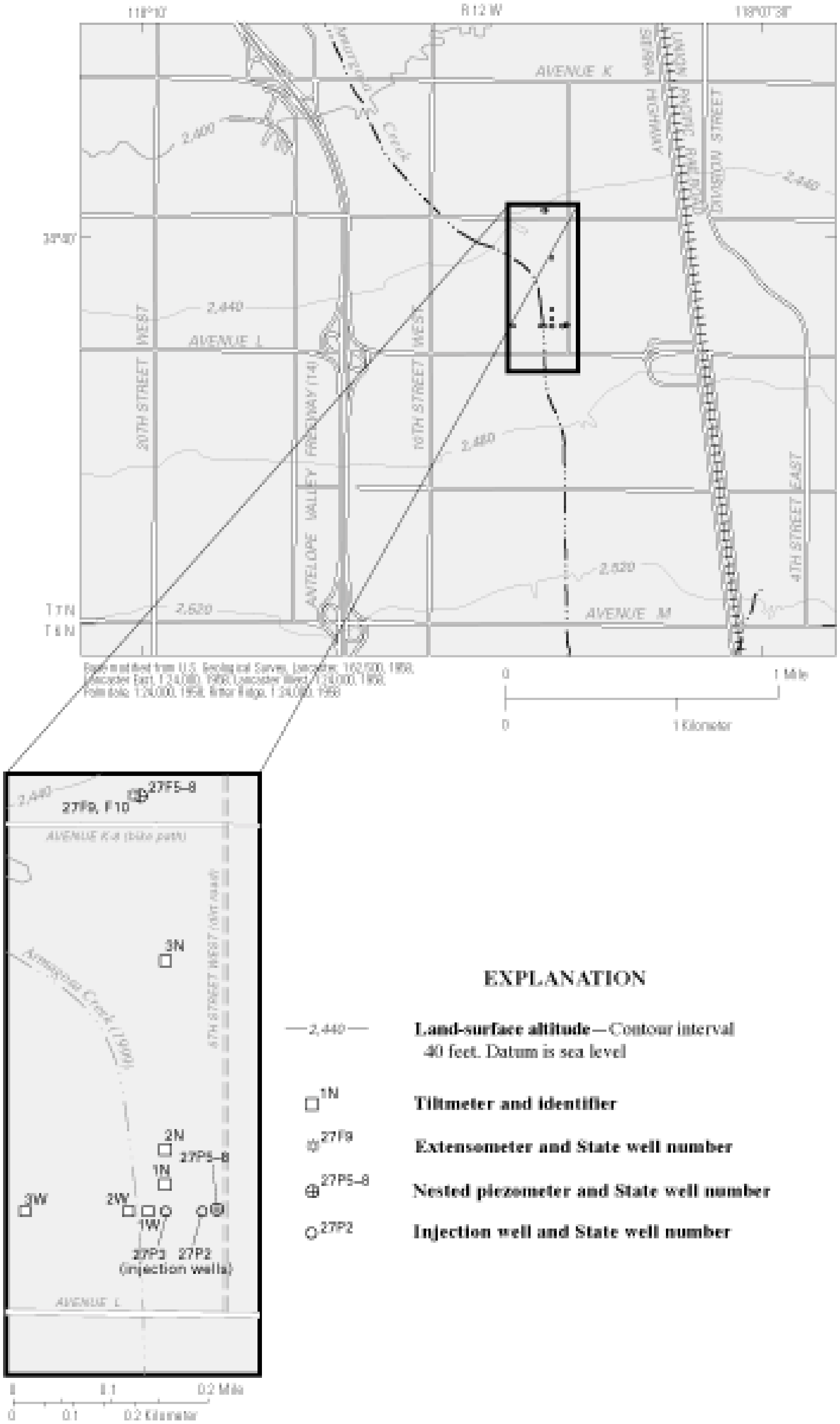

Figure 34. Locations of tiltmeters used to monitor the magnitude and direction of ground tilting associated with direct well injection during cycle 2 at Lancaster, Antelope Valley, California.

microradians (Robert Larson, Los Angeles County Department of Public Works, written commun., 1999).

The magnitude and direction of tilt recorded by the tiltmeters on the northern array during cycle 2 are shown in figure 36. Monitoring of tilt began on November 11, 1996 (about 1 day before the start of injection), and ended on January 30, 1997 (the 80th day of injection). Data for the first, second, and fourth days of data collection by tiltmeters 1N, 2N, and 3N, respectively, are not shown in figure 36 because of large fluctuations in the readings owing to the settling of sand beneath the tiltmeters (Robert Larson, Los Angeles County Department of Public Works, written commun., 1997). On November 25, 1996, less than 2 weeks into injection, tiltmeters in the western array were removed because a poor connection between the battery and the data logger prevented data from being recorded. The last 14 days of data recorded for tiltmeters in the northern array (January 17–30, 1997) are not shown in figure 36 because the computer program used for the analysis was limited to 9,999 readings. The plots from the LACDPW for those 14 days, however, showed essentially no movement (Robert Larson, Los Angeles County Department of Public Works, written commun., 1997).

WATER-CHEMISTRY MONITORING

Water chemistry was monitored during the study to assess the effects of injected water on local ground-water quality. Ground-water samples were collected

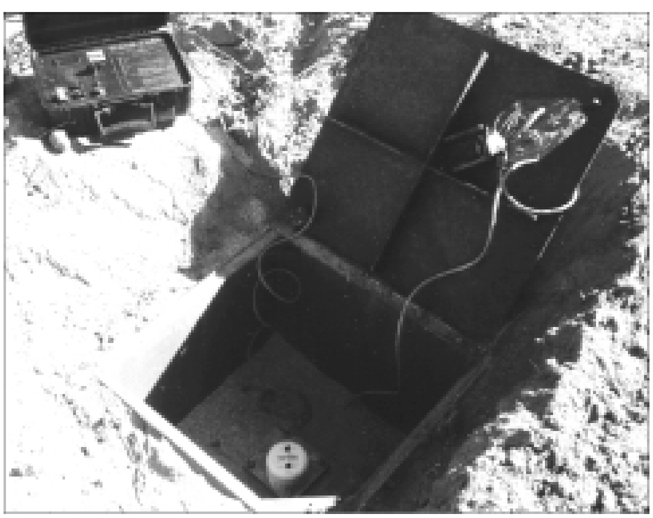

Figure 35. Typical tiltmeter installation for recording the magnitude and direction of ground tilting associated with direct well injection at Lancaster, Antelope Valley, California.

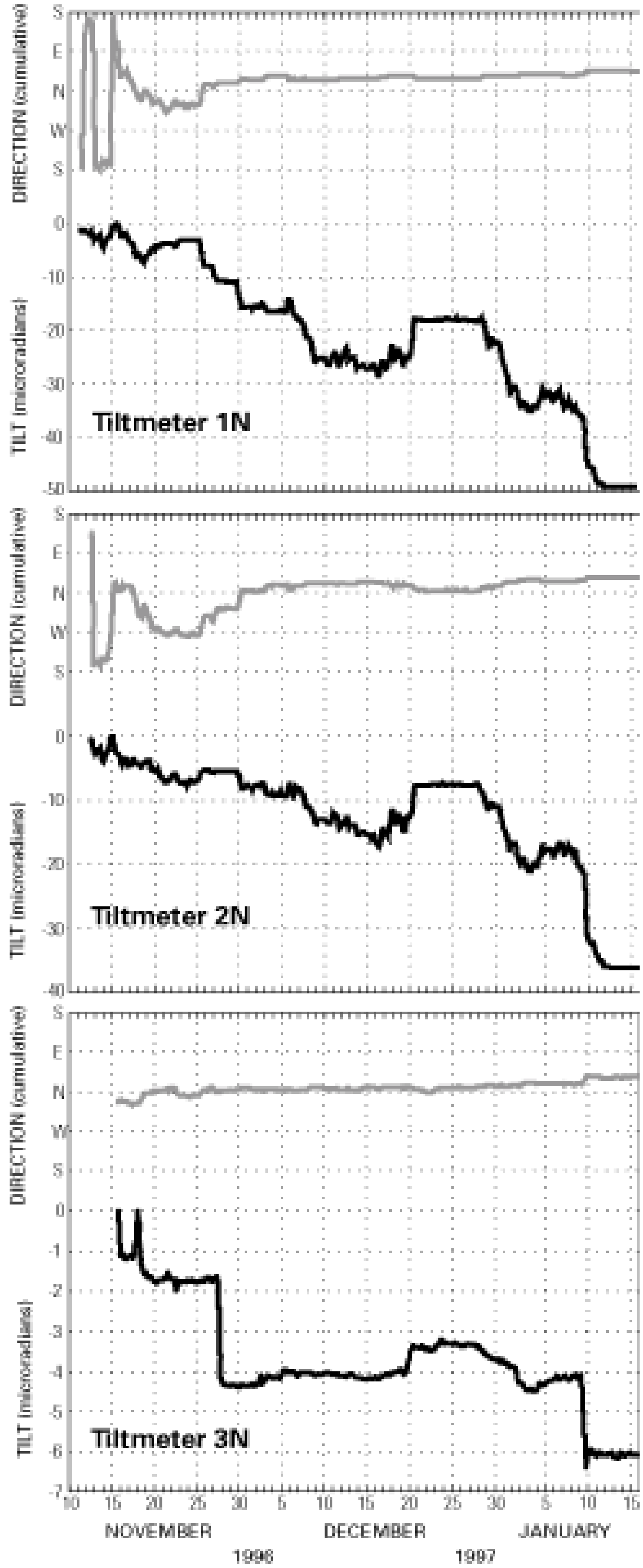

Figure 36. Magnitude and direction of tilt recorded during the injection phase of cycle 2 by tiltmeters 1N, 2N, and 3N in Lancaster, Antelope Valley, California. (From Robert Larson, Los Angeles County Department of Public Works, Materials Engineering Division, written commun., 1997)

from 2 injection wells, 15 production wells, and 5 piezometers (fig. 37) during and after injection, and imported surface-water samples were collected during injection. The samples were analyzed for major ions (table 9, at back of report), trace metals and metalloids (table 10, at back of report), and trihalomethanes (THMs) (table 11, at back of report). The ground-water samples are identified in tables 9–11 by the local well name (see table 1 for corresponding State well number). The imported surface-water samples are identified in the tables by the local well name of the injection well and the name of the water-importing agency: 7N/12W-27P2 [4-32 (AVEK)] and 27P3 [4-34 (AVEK)]. Analyses are presented only for water samples collected during cycles 1 and 2; analyses for water samples collected during cycle 3 will be included in a subsequent report (Miranda Fram, U.S. Geological Survey, written commun., 2000).

The frequencies of sample collection varied depending on (1) the target analyte, (2) the sample location, and (3) the cycle phase. Most of the water samples were collected from the injection wells; they were collected as frequently as daily during the recovery phases. THMs were the most frequently monitored constituents and were collected daily from several wells during the first 1 to 2 months of the recovery phases of cycles 1 and 2. The water samples from the 15 production wells generally were collected only once during each cycle phase. The three production wells (7N/12W-27H3, 27J4, and 27J6) at the Avenue K-8 and Division Street well field (fig. 3) were sampled daily during the first 1 to 2 months of the recovery phases. Water samples were collected from five piezometers once during both the pre-injection and storage phases of cycle 2.

Sample Collection Methods

Water samples were collected from the injection and production wells by personnel from the Los Angeles County Department of Agricultural Commissioner and Weights and Measures (abbreviated hereinafter as LAC). Water samples also were collected from the injection wells by personnel from AVEK as part of the quality-assurance program. Water samples were collected from the nested piezometers by personnel from the USGS.

Water samples from the injection and production wells were collected from a sampling port located on a horizontal part of the well discharge pipe and within several feet of the well head. Water samples from the nested piezometers were collected using a portable, piston-type, submersible pump to prevent aeration of the water during pumping. Prior to sampling, the well casings, the sampling ports, and the nested piezometer casings were purged of stagnant water. The injection and production wells not in operation at the time of sampling were pumped for several hours prior to sampling. The sampling ports were purged by allowing water to flow through the ports for several minutes. After purging, flow through the sampling port was adjusted to a steady rate to minimize aeration of the water. The nested piezometers were pumped until at least three casing volumes of water were purged and field measurements of pH, specific conductance, and temperature had stabilized (Wilde and Radtke, 1998; Wilde and others, 1998).

Water-chemistry samples were collected in glass and plastic bottles. The samples from nested piezometers were filtered through a 0.45-micrometer (μm) pore-size capsule filter during collection to remove sand and silt. The samples from the production wells were not filtered during collection, but were filtered in the laboratory through a 0.45-μm filter for the analysis of trace metals and metalloids, total dissolved solids, and ultraviolet absorbance (Maureen Smith, Antelope Valley–East Kern Water Agency, written commun., 1999; Wilhelmina Solinap, Los Angeles County Department of Agricultural Commissioner and Weights and Measures, Environmental Toxicology Laboratory, written commun., 2000). THM samples were preserved with sodium thiosulfate; cation and trace metals and metalloid samples were preserved with nitric acid; and total organic carbon samples were preserved with hydrochloric acid. Other chemical constituents did not require chemical preservation (Maureen Smith, Antelope Valley–East Kern Water Agency, written commun., 1999; Wilhelmina Solinap, Los Angeles County Department of Agricultural Commissioner and Weights and Measures, Environmental Toxicology Laboratory, written commun., 1999). All samples were chilled on ice and shipped to the respective LAC and AVEK laboratories.

Specific conductance, pH, water temperature, turbidity, free residual chlorine and total residual chlorine were measured on site for most samples collected from injection and production wells. On the occasions when LAC personnel were not able to make field measurements, specific conductance, pH, and turbidity were measured in the laboratory. Specific conductance, pH, water temperature, dissolved oxygen, and alkalinity were measured on site for samples collected from piezometers. Dissolved oxygen was measured with a flow-through chamber to isolate the sample from atmospheric oxygen.

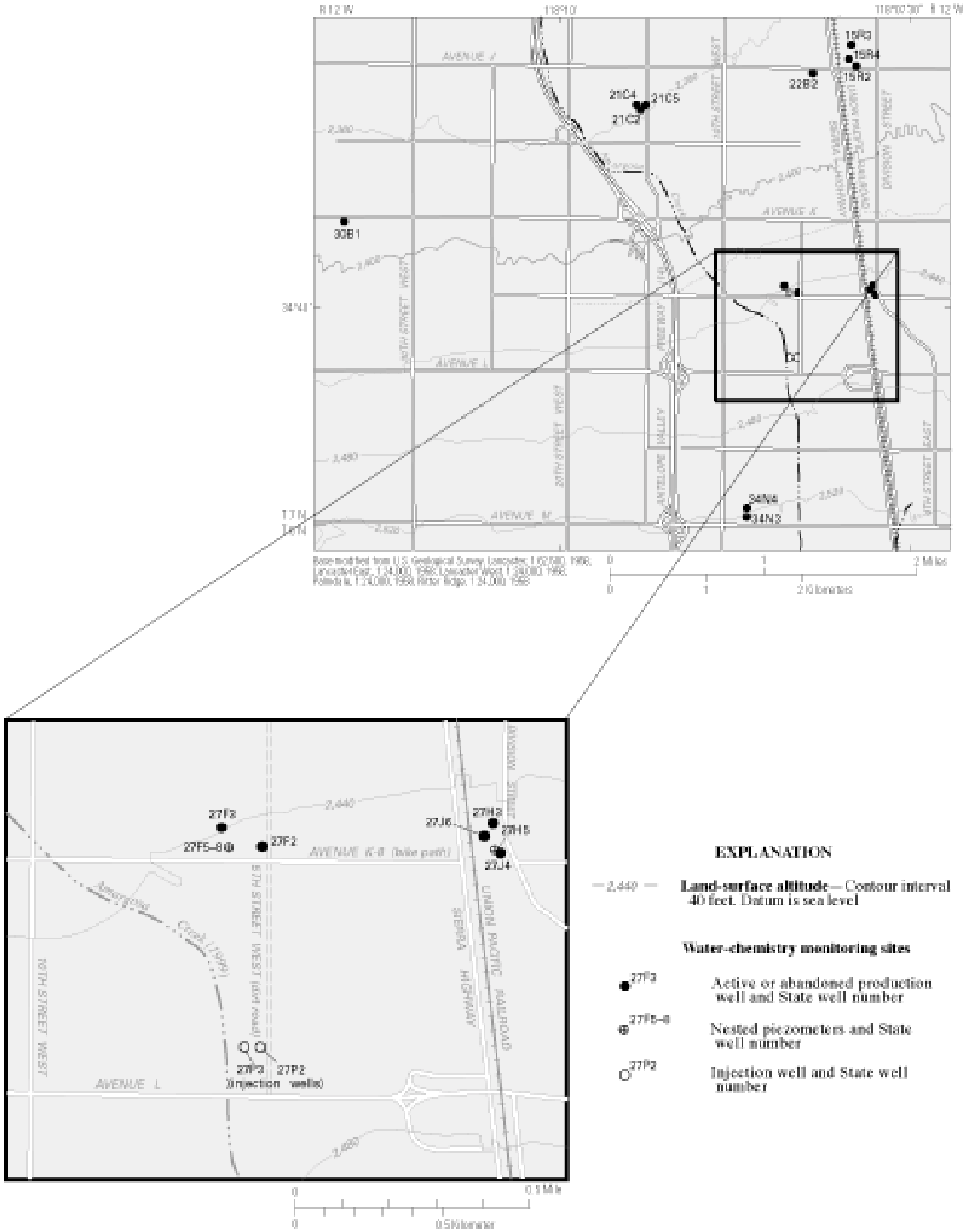

Figure 37. Locations of water-chemistry monitoring sites for cycles 1 and 2 of the injection, storage, and recovery study at Lancaster, Antelope Valley, California.

Table 12. Minimum reporting levels for physical properties and major ions, trace metals and metalloids, and trihalomethanes and associated parameters by agency and summary of analytical methods used to analyze water samples collected during cycles 1 and 2 of the injection, storage, and recovery study at Lancaster, Antelope Valley, California, April 1995 through January 1998

[USGS, U.S. Geological Survey; LAC, Los Angeles County Department of Agricultural Commissioner and Weights and Measures; AVEK, Antelope Valley–East Kern Water Agency; MBAS, Methylene Blue Active Substance. $CaCO_3$, calcium carbonate; $CHCl_2Br$, bromodichloromethane; $CHBr_3$, bromoform; $CHCl_3$, chloroform; $CHBr_2Cl$, dibromochloromethane; TTHM, total trihalomethanes. TON, threshold odor number; NTU, nephelometric turbidity unit; mg/L, milligram per liter; µS/cm, microsiemen per centimeter; °C, degrees Celsius; µg/L, microgram per liter; /cm, per centimeter. <, less than; na, not applicable]

Analytical method references:

Standard methods (SM)

All SMs are from "Standard Methods for the Examination of Water and Wastewater" (American Public Health Association, 1995)

U.S. Environmental Protection Agency (EPA) method number

EPA 300.0 A, "Methods for the Determination of Inorganic Substances in Environmental Samples" (U.S. Environmental Protection Agency, 1993)

EPA 415.1, "Methods for the Determination of Water and Wastes" (U.S. Environmental Protection Agency, 1983)

EPA 502.2, "Methods for the Determination of Organic Compounds in Drinking Water "(U.S. Environmental Protection Agency, 1988)

EPA 524.2, "Methods of the Determination of Organic Compounds in Drinking Water Supplement II" (U.S. Environmental Protection Agency, 1992)

U.S. Geological Survey Techniques of Water-Resources Investigations (USGS TWRI)

All methods are from chapter A6, Field Measurements (Wilde and others, 1998)

Property or constituent (Unit of measurement)	Minimum reporting level	Reporting agency	Analytical method reference
Physical properties and major ions			
Dissolved oxygen (mg/L)	0	USGS	USGS TWRI 6.2.1: Amperometric Method
pH (standard units)	0	LAC	SM 4500-H+ B: Electrometric Method
	0	AVEK	SM 4500-H+ B: Electrometric Method
	0	USGS	USGS TWRI 6.4: pH
Specific conductance (µS/cm)	1	LAC	SM 2510 B: Conductivity
	1	AVEK	SM 2510 B: Conductivity
	1	USGS	USGS TWRI 6.3: Specific Electrical Conductance
Temperature (°C)	na	LAC	SM 2550 B: Temperature
	na	USGS	USGS TWRI 6.1: Temperature
Hardness, total (mg/L as $CaCO_3$)	5	LAC	SM 2340 C: EDTA Titrimetric Method
Calcium, dissolved (mg/L)	2.0	LAC	SM 3500-Ca D: EDTA Titrimetric Method
Magnesium, dissolved (mg/L)	.1	LAC	SM 3500-Mg E: Calculation Method
Potassium, dissolved (mg/L)	.1	LAC	SM 3500-K D: Flame Emission Photometric Method
Sodium, dissolved (mg/L)	5.0	LAC	SM 3500-Na D: Flame Emission Photometric Method
Alkalinity, total (mg/L as $CaCO_3$)	4	LAC	SM 2320 B: Titration Method
	1	USGS	USGS TWRI 6.6.4.B: Inflection Point Titration Method
Chloride, dissolved (mg/L)	2.0	LAC	SM 4110 B: Ion Chromatography with Chemical Suppression of Eluent Conductivity
	2.0	AVEK	EPA 300.0 A: Suppressed Ion Chromatography
Fluoride, dissolved (mg/L)	.1	LAC	SM 4110 B: Ion Chromatography with Chemical Suppression of Eluent Conductivity
Sulfate, dissolved (mg/L)	.5	LAC	SM 4110 B: Ion Chromatography with Chemical Suppression of Eluent Conductivity
Nitrate (mg/L)	.03	LAC	SM 4110 B: Ion Chromatography with Chemical Suppression of Eluent Conductivity
Apparent color, unfiltered (units)	0	LAC	SM 2120 B: Visual Comparison Method
Odor threshold (TON)	0	LAC	SM 2150 B: Threshold Odor Test
Dissolved solids (mg/L)	5	LAC	SM 2540 C: Total Dissolved Solids Dried at 180 degrees Celsius
Turbidity (NTU)	<.1	LAC	SM 2130 B: Nephelometric Method
MBAS (mg/L)	.05	LAC	SM 5540 C: Anionic Surfactants as MBAS

Table 12. Minimum reporting levels for physical properties and major ions, trace metals and metalloids, and trihalomethanes and associated parameters by agency and summary of analytical methods used to analyze water samples collected during cycles 1 and 2 for the injection, storage, and recovery study at Lancaster, Antelope Valley, California, April 1995 through January 1998—Continued

Property or constituent (Unit of measurement)	Minimum reporting level	Reporting agency	Analytical method reference
Trace metals and metalloids			
Aluminum, dissolved (μg/L)	50	LAC	SM 3113 B: Electrothermal Atomic Absorption Spectrometric Method
Antimony, dissolved (μg/L)	6	LAC	SM 3113 B: Electrothermal Atomic Absorption Spectrometric Method
Arsenic, dissolved (μg/L)	2	LAC	SM 3113 B: Electrothermal Atomic Absorption Spectrometric Method
Barium, dissolved (μg/L)	100	LAC	SM 3113 B: Electrothermal Atomic Absorption Spectrometric Method
Beryllium, dissolved (μg/L)	1	LAC	SM 3113 B: Electrothermal Atomic Absorption Spectrometric Method
Cadmium, dissolved (μg/L)	1	LAC	SM 3113 B: Electrothermal Atomic Absorption Spectrometric Method
Chromium, total (μg/L)	10	LAC	SM 3113 B: Electrothermal Atomic Absorption Spectrometric Method
Copper, dissolved (μg/L)	50	LAC	SM 3113 B: Electrothermal Atomic Absorption Spectrometric Method
Iron, dissolved (μg/L)	100	LAC	SM 3111 B: Direct Air-Acetylene Flame Method
Lead, dissolved (μg/L)	5	LAC	SM 3113 B: Electrothermal Atomic Absorption Spectrometric Method
Manganese, dissolved (μg/L)	30	LAC	SM 3111 B: Direct Air-Acetylene Flame Method
Mercury, dissolved (μg/L)	1	LAC	SM 3112 B: Cold-Vapor Atomic Absorption Spectrometric Method
Nickel, dissolved (μg/L)	10	LAC	SM 3113 B: Electrothermal Atomic Absorption Spectrometric Method
Selenium, dissolved (μg/L)	5	LAC	SM 3113 B: Electrothermal Atomic Absorption Spectrometric Method
Silver, dissolved (μg/L)	10	LAC	SM 3113 B: Electrothermal Atomic Absorption Spectrometric Method
Thallium, dissolved (μg/L)	1	LAC	SM 3113 B: Electrothermal Atomic Absorption Spectrometric Method
Zinc, dissolved (μg/L)	50	LAC	SM 3111 B: Direct Air-Acetylene Flame Method
Trihalomethanes and associated parameters			
Ultraviolet absorbance (UV_{254}) (/cm)	0	AVEK	SM 5910 B: Ultraviolet Absorption Method (modified)
Free residual chlorine (mg/L)	trace	AVEK	SM 4500-Cl G: DPD Colorimetric Method
Total residual chlorine (mg/L)	0.1	LAC	SM 4500-Cl G: DPD Colorimetric Method
	trace	AVEK	SM 4500-Cl G: DPD Colorimetric Method
Total organic carbon (mg/L)	1.0	LAC	EPA 415.2: UV Promoted Oxidation Method
	.5	AVEK	SM 5310 C: Persulfate-Ultraviolet Oxidation Method
$CHCl_2Br$ (μg/L)	.5	LAC	EPA 524.2: Capillary Column Gas Chromatography - Mass Spectrometry
	.5	AVEK	EPA 502.2: Restek 502.2 column, purge, and trap EICD
$CHCl_2Br$ Formation Potential (μg/L)	.5	LAC	SM 5710 B: Trihalomethane Formation Potential (THMFP)
$CHBr_3$ (μg/L)	.5	LAC	EPA 524.2: Capillary Column Gas Chromatography - Mass Spectrometry
	.5	AVEK	EPA 502.2: Restek 502.2 column, purge, and trap EICD
$CHBr_3$ Formation Potential (μg/L)	.5	LAC	SM 5710 B: Trihalomethane Formation Potential (THMFP)
$CHCl_3$ (μg/L)	.5	LAC	EPA 524.2: Capillary Column Gas Chromatography - Mass Spectrometry
	.5	AVEK	EPA 502.2: Restek 502.2 column, purge, and trap EICD
$CHCl_3$ Formation Potential (μg/L)	.5	LAC	SM 5710 B: Trihalomethane Formation Potential (THMFP)
$CHBr_2Cl$ (μg/L)	.5	LAC	EPA 524.2: Capillary Column Gas Chromatography - Mass Spectrometry
	.5	AVEK	EPA 502.2: Restek 502.2 column, purge, and trap EICD
$CHBr_2Cl$ Formation Potential (μg/L)	.5	LAC	SM 5710 B: Trihalomethane Formation Potential (THMFP)
TTHM (μg/L)	.5	LAC	EPA 524.2: Capillary Column Gas Chromatography - Mass Spectrometry
	.5	AVEK	EPA 502.2: Restek 502.2 column, purge, and trap EICD
TTHM Formation Potential (μg/L)	.5	LAC	SM 5710 B: Trihalomethane Formation Potential (THMFP)

Analytical Methods

The samples collected from the injection and production wells by LAC personnel and from the nested piezometers by USGS personnel were analyzed at the Los Angeles County Department of Agricultural Commissioner and Weights and Measures Environmental Toxicology Laboratory. The samples collected by AVEK personnel were analyzed at the Antelope Valley–East Kern Water Agency Laboratory. Laboratory analyses and field measurements were done according to the referenced methods listed in table 12.

Quality control of laboratory analyses consisted of a combination of calibration standards, equipment and sample blanks, matrix spikes, matrix-spike duplicates, and duplicate samples. The number of quality-control samples run with each batch of samples depended on the analytical method. For example, duplicates, spikes, and blanks each accounted for about 10 percent of the total number of samples analyzed by AVEK for THMs, chloride, and total organic carbon (Maureen Smith, Antelope Valley–East Kern Water Agency, written commun., 2001). If the acceptable ranges for the quality control samples were exceeded, the analytical results of the collected samples were rejected and the samples reanalyzed. Acceptable ranges for the quality-control samples were plus or minus 10 percent for major ions, plus or minus 25 percent for trace metals and metalloids, and plus or minus 20 percent for THMs (Los Angeles County Department of Public Works, 2000; Maureen Smith, Antelope Valley–East Kern Water Agency, written commun., 2001).

FLOW-RATE MONITORING

Flow rates at the injection wells were monitored with electromagnetic bi-directional flowmeters (fig. 38) to estimate the volumes of injected and extracted water and to help maintain a constant rate of flow. The flowmeters were accurate to 0.5 percent of flow rate. The flowmeters were installed within a straight segment of each well's discharge pipe to avoid turbulent flow that could cause inaccurate readings. Flow rates were output to digital displays on each flowmeter and at remote enclosures in an electrical control panel near injection well 7N/12W-27P2. The combined flow rate and cumulative volume was displayed on a separate remote enclosure when both wells were operating simultaneously.

Data Collection

Flowmeter output initially was recorded on a data logger at the extensometer site. Flowmeter data were recorded at time intervals ranging from 1 to 15 minutes. In November 1996, prior to the beginning of cycle 2, a data logger was installed at the injection site owing to concerns about potential signal degradation between the flowmeters and the data logger at the extensometer site. The flow rates recorded on the data logger at the extensometer site were as much as 2.5 percent less than the flow rates recorded on the data logger at the injection site. The flow rates recorded on the data logger at the injection site were comparable to real-time flow rates displayed at both flowmeters and at the remote enclosures at the electrical control panel. Therefore, only data from the data logger at the injection site for cycles 2 and 3 are shown in this report.

Data Processing

Flowmeter data were downloaded from the data logger to a laptop computer during the weekly or bimonthly field visits from April 1996 through September 1998. Following each field visit, the data were entered into the USGS NWIS database. Flowmeter output (in millivolts) was recorded separately for each injection well and then converted to flow rates in gallons per minute using the relation derived from a least-squared regression of the calibration data:

$$FL = 0.9375(V) + (-375), \qquad (3)$$

where

FL is the computed flow rate, in gallons per minute;

0.9375 is the slope of the least-squares regression equation, in gallons per minute per millivolt;

V is the flow meter output, in millivolts; and

–375 is the offset (y-intercept) of the least-squares regression equation, in gallons per minute.

Injection and extraction flow rates for the period April 1996 through September 1998 are shown in figure 39.

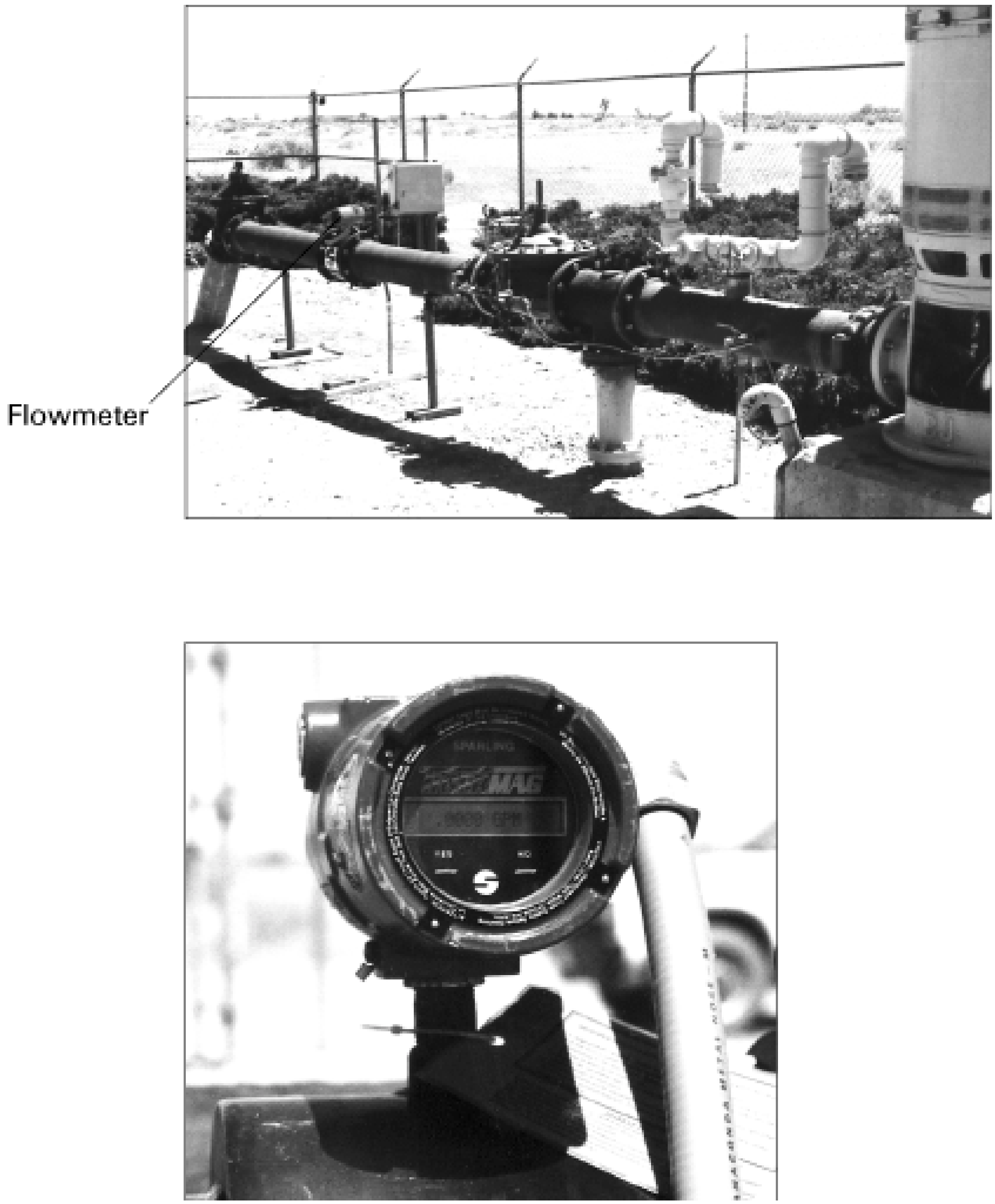

Figure 38. Flowmeter used to measure injection and extraction flow rates at injection well 7N/12W-27P3 in Lancaster, Antelope Valley, California.

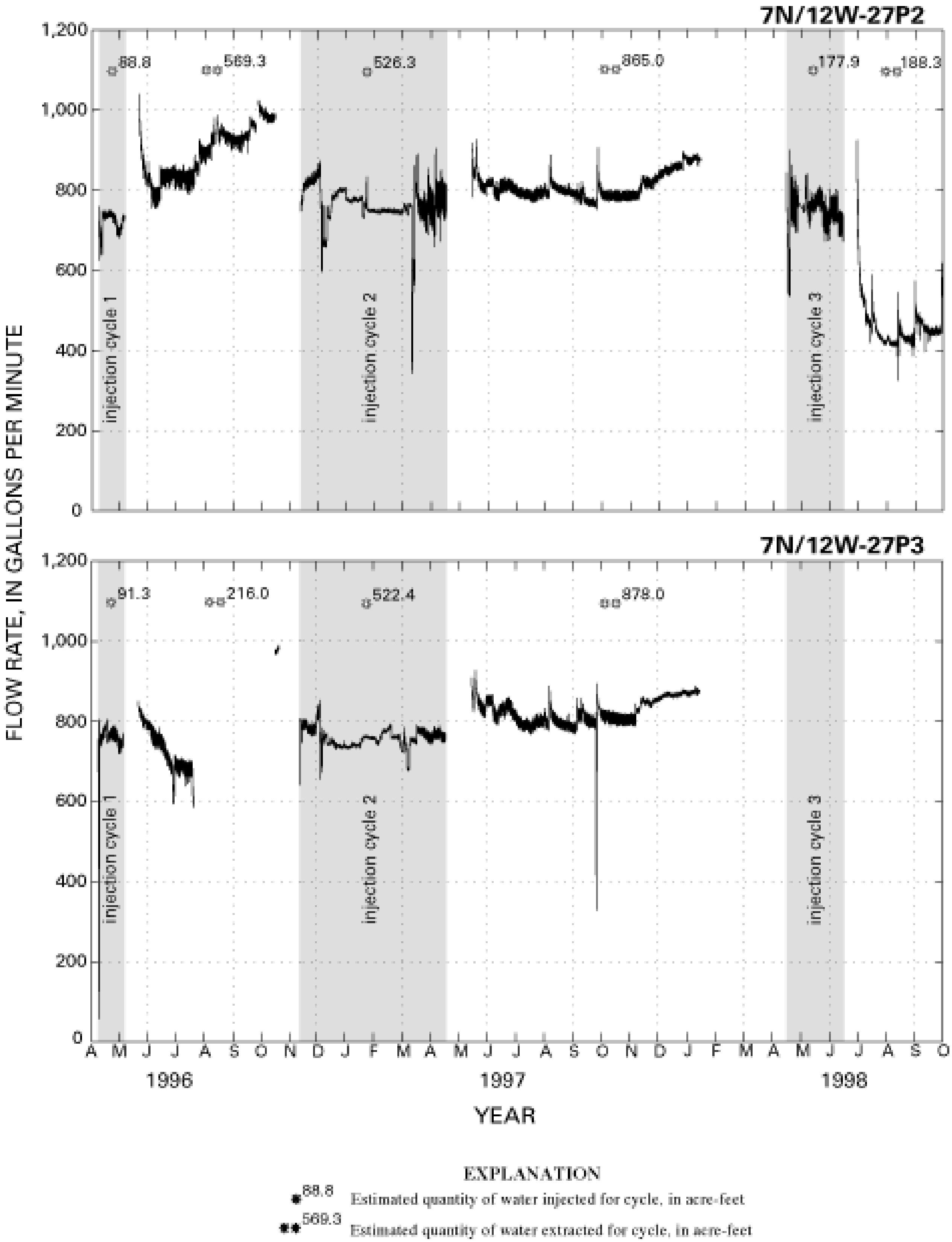

Figure 39. Injection and extraction flow rates at injection wells 7N/12W-27P2 and 27P3 in Lancaster, Antelope Valley, California, April 1996 through September 1998.

SUMMARY

A series of freshwater injection, storage, and recovery tests was done 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 consisted of three cycles of injection, storage, and recovery. Data were collected from various networks established to monitor vertical deformation of the aquifer system, water-level fluctuations, land-surface deformation, water chemistry, and injection and extraction flow rates.

Data were collected from a dual extensometer, 10 nested 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. Vertical deformation, barometric pressure, and flow rates were monitored continuously. Water levels were continuously measured in some piezometers and wells and periodically measured in others. Microgravity surveys and geodetic surveys (differential leveling, GPS, and tiltmeter) generally were conducted during periods of direct well injection.

This report presents descriptions of direct well injection site selection and test design; installation of the various monitoring networks; instrumentation; methods of data collection, processing, and analysis; and lithologic and geophysical logs. It also provides illustrations of extensometer and nested piezometer construction, and graphic and tabular presentations of the data. It is one of five U.S. Geological Survey reports describing a series of injection tests at Lancaster, California, which were designed to assess the feasibility of implementing an injection program as part of a management strategy to halt the decline of ground-water resources and avoid future land subsidence.

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APPENDIX A. DISCUSSION ON PREPARING FOR A MICROGRAVITY SURVEY

Prior to the start of each microgravity survey, the gravity meter was taken to the Quartz Hill bedrock reference station for adjustment, referred to as reranging, to bring the range of the fine nulling dial to within the range of the gravitational force at Quartz Hill. The reranging procedure, however, created considerable oscillation (hysteresis) in the springs of the meter resulting in erratic instrument drift and making it difficult, if not impossible, to measure gravity accurately at the microGal-level for several hours after the procedure. During this period of erratic instrument drift, the gravity meter was used to determine the relative differences between stations on the periphery of the injection area and Quartz Hill. Once drift had subsided, the cross and long levels on the meter (fig. 22) and meter sensitivity were field checked. If the cross level is not adjusted correctly, the meter will not measure the full force of gravity, and if the sensitivity is set too low, valuable time will be wasted waiting for the meter to find null. All gravity meter operators should know how to perform these checks and adjustments as described by the LaCoste and Romberg (1997) instruction manual. We suggest one additional check that was not included in the manual; this step pertains to the electrostatic nulling device. If the device is to be used, the sensitivity checks should be done with the nulling device enabled, but not operating. There are two switches on the nulling device, one labeled “E” (enable) and “D” (disable) and the other labeled “R” (run) and “O” (off); they should be set to E and O positions.

Once the cross and long levels and meter sensitivity have been checked, a preliminary survey should be made to determine values of the nulling dial for all stations. This is done first by leveling the meter for any given station and then by releasing the internal beam of the gravity meter. Next, turn on the reading lamp and look into the microscope eyepiece; the shadow of the beam will be visible on one side or the other of the reading line. If the beam is to the left of the reading line, turn the nulling dial clockwise; if the beam is to the right of the reading line, turn the nulling dial counterclockwise. The nulling dial should be turned smoothly in full revolution increments, always ending at zero, until the beam shadow reaches the reading line. Always turn off the incandescent reading lamp as soon as possible because the excess heat can induce mechanical hysteresis in the springs and levers from thermal expansion. Once a dial value is determined for a station, this value should be used for all subsequent measurements at that station. This eliminates introduction of screw calibration errors (circular error in the machining of the screw) into the measured difference for a station from one survey to another. When two adjacent stations had similar dial values, we used an average dial value for both. This precaution eliminates the introduction of screw calibration errors into the measured difference between the adjacent stations. This “quiet” operation uses only the electrostatic nulling device to measure gravity between the adjacent stations. This operation is termed quiet because the noise of spring hysteresis from turning the nulling dial is avoided.

APPENDIX B. DISCUSSION ON MAKING A MICROGRAVITY MEASUREMENT

Upon reaching the station to be measured, the carrying case should be gently set on the ground within 2 ft of the station. To minimize possible jarring motions, the meter operator should kneel on foam knee pads while moving the meter from its carrying case to the gravity station. Great care must be taken when setting the meter on the station. The operator should cradle the meter with both hands and then, with elbows on the ground, set the reference leg into the central divot of the gravity station. The remaining two legs should be positioned with great care. If the operator is able to hear the meter legs touching the station, insufficient care was taken in handling the instrument.

Once the meter is nestled onto the bronze tablets, it can be leveled. The reference leg should have a locking nut on it; the leveling of the meter is done using the remaining two legs. The quickest method of leveling the meter is to level the cross level first and then the long level. After the meter is level, the internal beam can be released by turning the arrestment knob counterclockwise. Extreme care must be taken once the beam is released. Accidentally bumping the meter can severely damage internal parts, rendering the meter inoperable. If the preset dial reading is correct, the beam should approach the null position within 30 seconds. The null position can be observed on the electronic galvonometer (voltage indicator) when the needle is centered or by viewing the beam shadow through the microscope eyepiece. Once the needle is centered or the beam shadow is very near the reading line, the electrostatic nulling device can be enabled and then turned on. First toggle the switch labeled E and D to the enable (E) position and then toggle the switch labeled R and O to the run (R) position. At this point, the station identifier, the dial counter reading, the time when the nulling device was turned on, and any atmospheric and (or) anthropogenic disturbances should be recorded.

The nulling device needs a 4- to 7-minute waiting period after activation to allow spring hysteresis to dissipate and to establish a constant rate of change in the digital output. During the waiting period, the data logger can be turned on. Starting a few minutes after the nulling device is activated, the averaged (for 20 measurements) filtered gravity output (in millivolts) and standard deviation (in millivolts) should be recorded manually at 1-minute intervals even though they also may be recorded digitally. This allows the gravity meter operator to monitor the trend, or the lack thereof, of the output. For this study, the gravity meter was allowed to stabilize for 5 minutes before each measurement. Once a consistent rate of change (1 to 5 millivolts per minute) and an acceptable standard deviation (1 millivolt or less) are recorded, the operator can be confident that the measurement is good. At this point, the electrostatic nulling device can be turned off, but left enabled. The data logger should also be turned off. Before the beam is clamped down to prevent it from bouncing during transport, the dial counter should be set for the next station. When turning the nulling dial, turns should be made smoothly without jerking the meter. Furthermore, the desired dial counter reading should always be obtained by turning the nulling dial in a clockwise direction. If the desired value is less than the present value, the operator will turn the nulling dial counterclockwise past the desired value at least one full revolution, then clockwise until reaching the desired value, being careful not to go past that value. If the desired value is inadvertently passed, even slightly, the nulling dial should be turned counterclockwise again one full turn and then turned clockwise until reaching the desired value. Care should be taken the first time, because the back and forth turning of the dial introduces unnecessary noise (spring hysteresis) into the next measurement. Once the dial is set, the internal beam can be clamped down.

Clamping the beam before moving the meter is absolutely critical. Clamping the beam also reduces the random oscillations induced by turning the nulling dial. Once the beam is clamped, the meter can safely be moved back to the carrying case and on to the next station. If gravity stations are within walking distance, the meter should be hand carried between stations. If a motorized vehicle is to be used, the driver should exercise care to avoid sudden stops, potholes, and uneven sections of the road. The best solution for a smooth ride is to have a person hold the meter while in transit.

APPENDIX C. DISCUSSION ON SOURCES OF MICROGRAVITY SURVEY ERRORS

Nonlinear instrument drift can be a major source of microgravity survey error. One of the primary causes of nonlinear drift is jostling the meter during transport. The effects of jostling, however, can be minimized by transporting the meter in a soft carrying case, by having someone hold the meter while in transit, and by using a smooth-riding vehicle. A soft carrying case is especially critical because it reduces the effects of bumps and vibrations on the meter during transit between stations. The gravity meter used for this study was transported in a soft carrying case constructed of open-cell foam. The case also was used to organize the data logger, data storage module, keyboard/display, two 12-V, 6.5 Amp-Hour (AHr) batteries, and an electronic barometer so that packing and unpacking time was minimized between measurements. The extra weight (19 pounds) of these accessories, plus the 7.7-pound weight of the gravity meter, also helped soften the jolts and high-frequency vibrations encountered during transit.

Another source of nonlinear drift is variation in the temperature of the gravity meter. Although the gravity meter has a thermostat and an internal heating element, temperature variations can occur during a survey. Several steps can be taken to minimize the variations; they include (1) protecting the meter from direct sunlight (For this study, the meter was shaded either by the operator or by a white cardboard box.); (2) not leaving the meter in a vehicle where ambient temperature can rise quickly; (3) using predetermined dial values for each station thereby eliminating use of the meter's incandescent reading lamp, which is a considerable source of heat; (4) turning on the meter and the nulling device several days before a survey to allow thermal stabilization of the meter; and (5) leaving the electronic nulling device enabled (E) for the duration of the survey.

Barometric effects also are a source of nonlinear drift. Gravity meters normally are sealed and protected from barometric effects by an O-ring; but on older meters, or meters that have not been factory serviced for at least 10 years, the O-ring can be cracked. Despite a buoyancy compensator in the beam mechanism, a failing O-ring can cause differential barometric loading on the beam mass and result in nonlinear instrument drift over time. For this study, each survey loop, which began and ended at the GR reference station and was completed two times, was restricted to three or four stations to limit measurement time to 2 to 3 hours. Minimizing the time spent on each loop minimized the effects of nonlinear drift owing to temporal changes in barometric pressure. Survey loops that required more than 3 hours generally produced unacceptable drift rates. Surveys loops done during the passage of a weather front and an abrupt change in barometric pressure also usually produced unacceptable drift rates.

Wind can produce unwanted effects on a gravity meter. As the meter is buffeted by the wind, it can be tipped out of plumb, reducing the gravity measurement. Wind also can cause the beam and springs to oscillate, introducing noise into the measurement. During this study a white cardboard box was used to shield the meter from the wind and the sun. Two of the box flaps were cut off so that handling the box was easier. Great care was taken not to bump the meter while covering or uncovering it. The remaining two flaps were weighted to prevent the box from moving. A small window was cut in the top of the box so that the meter levels, reading galvonometer, and counter dial could be viewed when the meter was covered.

Earthquakes, even distant large earthquakes, can render a gravity meter inoperable for hours or even days. If the galvonometer needle and levels behave erratically (swinging wildly from side to side), the gravity meter operator should suspect seismicity as the cause. To confirm or dismiss seismicity as a cause, the operator can call the U.S. Geological Survey National Earthquake Information Center (NEIC) in Golden, Colorado, at (800) 525-7848. The epicenters and magnitudes of earthquakes are determined rapidly by the USGS and information on an earthquake is quickly available to the general public.

On November 6, 1996, during a microgravity survey for this study, the needle of the galvonometer was observed swinging erratically. A call was made to the NEIC which confirmed an earthquake of a magnitude greater than 7 in the Bonin Islands 375 mi south of Tokyo, Japan. Resonance ringing was observed for nearly 1 hour. The survey loop that was in progress at the time of the earthquake was abandoned, and subsequent survey loops that same day produced unacceptable results. On the following day, the meter performed normally.

Solar flare activity can affect meter readings. Bursts of solar radiation produced by solar flare activity can interfere with the electrostatic nulling device. While these effects are not immediately obvious to the operator, the effects become clear when the field data are reduced (solid earth tides removed). Significant solar flare activity was thought to be the cause of unacceptable instrument drift for two survey loops conducted on April 9, 1997. Survey loops on the following day were successful.

Electromagnetic fields from radio station transmitters and two-way field radios can affect the electrostatic nulling device and (or) the galvonometer. Two-way radios should be turned off while surveying. Surveying near powerful radio transmitters should be avoided altogether. The effects of frequent, low-flying military aircraft over a study area during surveys are unknown.

Underground utilities including buried phone lines, high-voltage alternating current (AC) power lines, and water mains can adversely affect the operation of the meter. To avoid these potential sources of survey error, locations of underground utilities should be identified and gravity stations should be constructed as far away from them as possible. Within the contiguous United States, a phone call to Underground Service Alert will notify all the pertinent utilities. The utility companies will then locate and mark their buried lines and (or) pipes within the area in question.

Tables 9–11 Follow this page

Link to table 9.

Link to table 10.

Link to table 11.