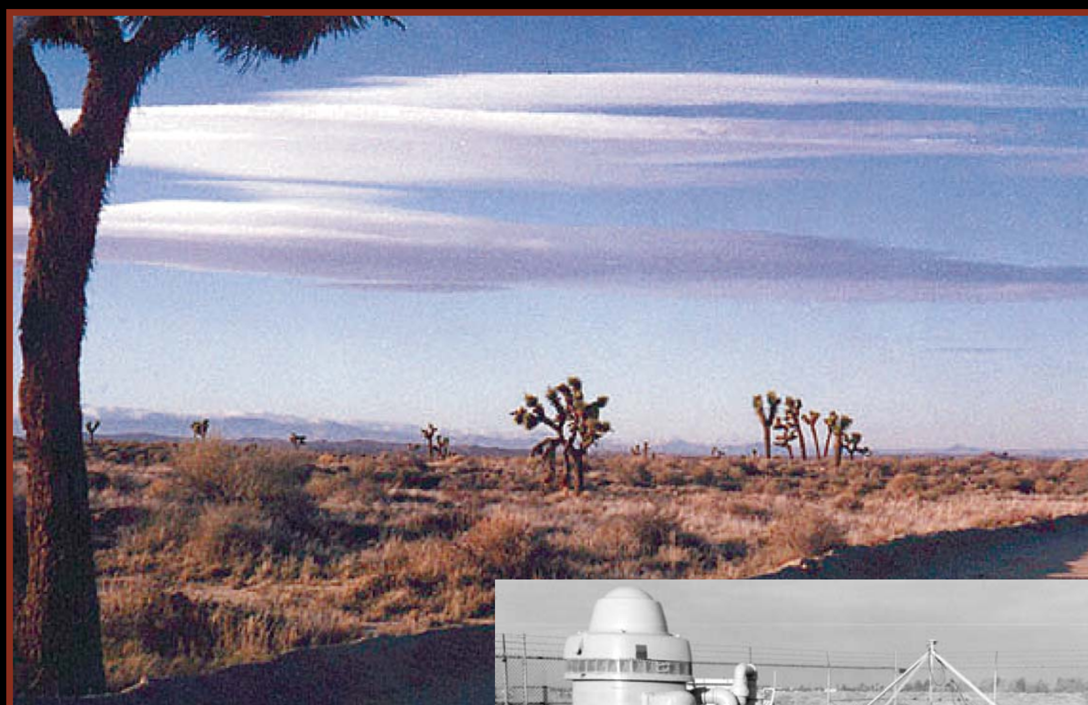
Determination of Specific Yield and Water-Table Changes Using Temporal Microgravity Surveys Collected During the Second Injection, Storage, and Recovery Test at Lancaster, Antelope Valley, California, November 1996 through April 1997



U.S. Geological Survey
Water-Resources Investigations
Report 03-4019

Prepared in cooperation with the **Los Angeles County Department of Public Works** and the **Antelope Valley-East Kern Water Agency**

PWS-0209-0001

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By James F. Howle, Steven P. Phillips, Roger P. Denlinger, *and* Loren F. Metzger

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ANTELOPE VALLEY–EAST KERN WATER AGENCY

Sacramento, California
2003

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

CONVERSION FACTORS

Multiply	By	To obtain
acre-foot (acre-ft)	0.001233	cubic hectometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared (ft^2)	0.09290	meter squared
gallon per minute (gal/min)	0.06309	liter per second
inch	2.54	centimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	259.0	hectare

VERICAL 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 both the United States and Canada, formerly called Sea Level Datum of 1929.

ABBREVIATIONS

g/cm^3	gram per cubic centimeter
m	meter
mGal	milligal
mm	millimeter
μGal	microgal
μGal/m	microgal per meter

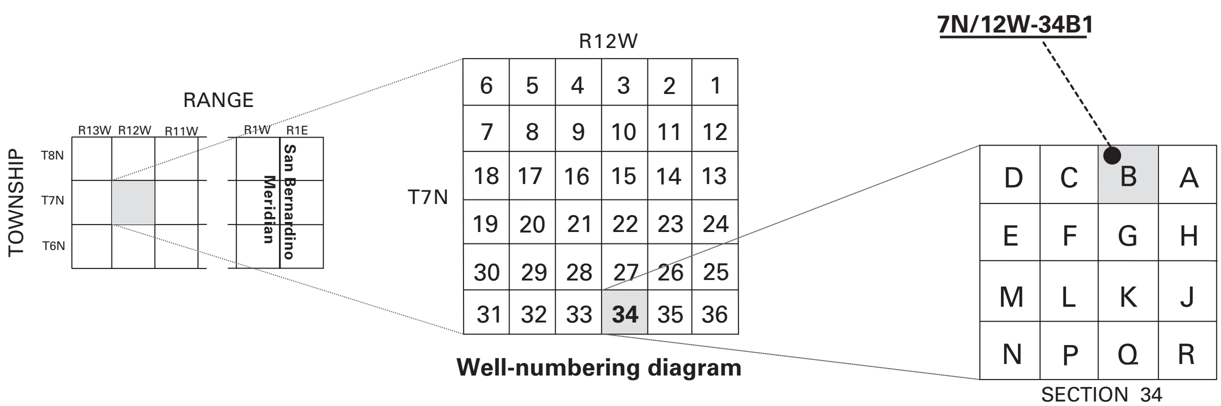
AVEK	Antelope Valley–East Kern Water Agency
InSAR	Interferometric Synthetic Aperture Radar
LACDPW	Los Angeles County Department of Public Works
SWP	State Water Project
USGS	U.S. Geological Survey

ABBREVIATED GRAVITY UNITS

Milligal (mGal) is defined as 10^{-3} centimeter per second squared and is equal to 3.281×10^{-5} feet per second squared. A microgal (μGal) is defined as 10^{-6} centimeter per second squared and is equal to 3.281×10^{-8} feet per second squared. Gram per cubic centimeter is a measure of density.

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

Determination of Specific Yield and Water-Table Changes Using Temporal Microgravity Surveys Collected During the Second Injection, Storage, and Recovery Test at Lancaster, Antelope Valley, California, November 1996 through April 1997

By James F. Howle, Steven P. Phillips, Roger P. Denlinger, *and* Loren F. Metzger

ABSTRACT

To evaluate the feasibility of artificially recharging the ground-water system in the Lancaster area of the Antelope Valley, California, the U.S. Geological Survey, in cooperation with the Los Angeles County Department of Public Works and the Antelope Valley–East Kern Water Agency, conducted a series of injection, storage, and recovery tests between September 1995 and September 1998. A key component of this study was to measure the response of the water table to injection, which was difficult because the water table averaged 300 feet below land surface. Rather than install many expensive piezometers, microgravity surveys were conducted to determine specific yield and to measure the development of a ground-water mound during the injection of about 1,050 acre-feet of fresh water into an alluvial-aquifer system. The surveys were done prior to, during, and near the end of a 5-month injection period (November 12, 1996, to April 17, 1997). Results of the surveys indicate increases in gravity of as much as 66 microgals between a bedrock reference station and 20 gravity stations within a 1-square-mile area surrounding the injection site. The changes were assumed to have been caused by changes in the ground-water elevation.

Gravity and ground-water levels were measured simultaneously at an existing well (7N/12W-34B1). The coupled measurements were used to calculate a specific yield of 0.13 for the alluvial aquifer near the well. To determine the gravitational effect of the injection mound on the gravity measurements made near well 7N/12W-34B1, a two-dimensional gravity model was used. Results of the model simulation show that the effect on gravity associated with the mass of the injection mound was minor and thus had a negligible effect on the calculation of specific yield. The specific yield of 0.13, therefore, was used to infer water-level changes at other gravity stations within the study area. The gravity-derived water-level changes were compared with simulated water-table changes.

Gravity changes determined from the temporal microgravity surveys were analyzed to obtain the accumulated mass within the unconfined aquifer. The accumulated mass was reduced to a gravity-derived injection rate and compared with the measured injection rate to determine if the gravity changes reflect the volumetric response to injection.

INTRODUCTION

Historically, ground-water withdrawals from the alluvial-aquifer system in the Lancaster area of the Antelope Valley in southern California (fig.1) have exceeded natural replenishment, resulting in overdraft and land subsidence. Since the 1920s, ground-water levels have declined as much as 200 ft in the study area,

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and land subsidence has exceeded 6 ft (Ikehara and Phillips, 1994). Reliance on ground water eased somewhat in the 1970s because of 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.

From September 1995 through April 1998, 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 research and monitoring during three cycles of injection, storage, and recovery in the Lancaster area of the Antelope Valley, California, to evaluate the feasibility of artificially recharging the ground-water system. A cycle consists of three periods: an injection period during which water is injected into the aquifer through a well, a storage period during which the well is idle, and a recovery period during which water is extracted from the aquifer by pumping from the same well. The objectives of the study were to develop a better understanding of the alluvial aquifer system; to assess the effects of injection, storage, and recovery on the aquifer system; and to develop tools to help plan and manage a larger injection program. The role of the USGS in this study was to collect and analyze hydraulic and aquifer-system deformation data, to develop a simulation/optimization model for use in designing and managing a larger scale injection program, and to determine the factors controlling the formation and fate of trihalomethanes (disinfection by-products) in the aquifer system.

This report presents the determination of specific yield and water-table changes using temporal microgravity surveys made during the second injection, storage and recovery test, November 1996 to April 1997. Microgravity data were collected during both the second and third cycles of the injection, storage, and recovery tests (Metzger and others, 2002); however, only data from the second cycle were analyzed for this report. Data from the third cycle could not be analyzed because of a 2-month delay in the start of the injection after the pre-injection gravity survey was completed, a week long interruption in the injection, and a significantly reduced injection rate for a shorter period of time than that for cycle 2.

The microgravity surveys were done as an alternative to installing many monitoring wells to measure water-level changes resulting from the injection test. Because of the depth of water in the study area, which averaged 300 ft below land surface, the cost to install the number of wells needed to define the shape of ground-water mounding near the injection site was prohibitive. The microgravity surveys measure changes in mass beneath gravity stations resulting from the freshwater injection. One of the gravity stations was located near an observation well, which allowed gravity changes to be correlated with water-level changes to estimate a specific yield for the alluvial aquifer. Using the gravity-derived specific yield, water-table changes in the vicinity of the injection wells were estimated on the basis of the measured gravity changes. This report presents the results of those surveys.

A companion report by Metzger and others (2002) presents the data collected during injection, storage, and recovery tests between September 1995 and September 1998. Analytical methods and data collected for the investigation of the formation and fate of trihalomethanes during the third cycle of the injection, storage, and recovery test are described in a report by Fram and others (2002). Subsequent reports describe the processes affecting the trihalomethane concentrations associated with the third injection, storage, and recovery test (Fram and others, 2003) and the development of a simulation/optimization model for use in designing and managing a regional scale injection program (Phillips and others, 2003).

Description of Study Area

The study area encompasses about 1 mi^2 just south of the city of Lancaster, Antelope Valley, California (figs. 1 and 2). Lancaster is in the south-central part of the valley in the western part of the Mojave Desert and is about 50 mi north of Los Angeles. The study area is on an alluvial fan that slopes gently northwestward at a gradient of about 60 ft/mi and ranges in elevation from about 2,480 ft above sea level on the southern side of the study area to about 2,440 ft on the northern side at Avenue K. Annual rainfall at Lancaster averaged about 8.0 inches for 1974–98 (Western Regional Climate Center, accessed July 10, 1999). Amargosa Creek, an ephemeral channel, trends north and then northwest through the study area (fig. 2) and generally flows only after periods of intense rainfall.

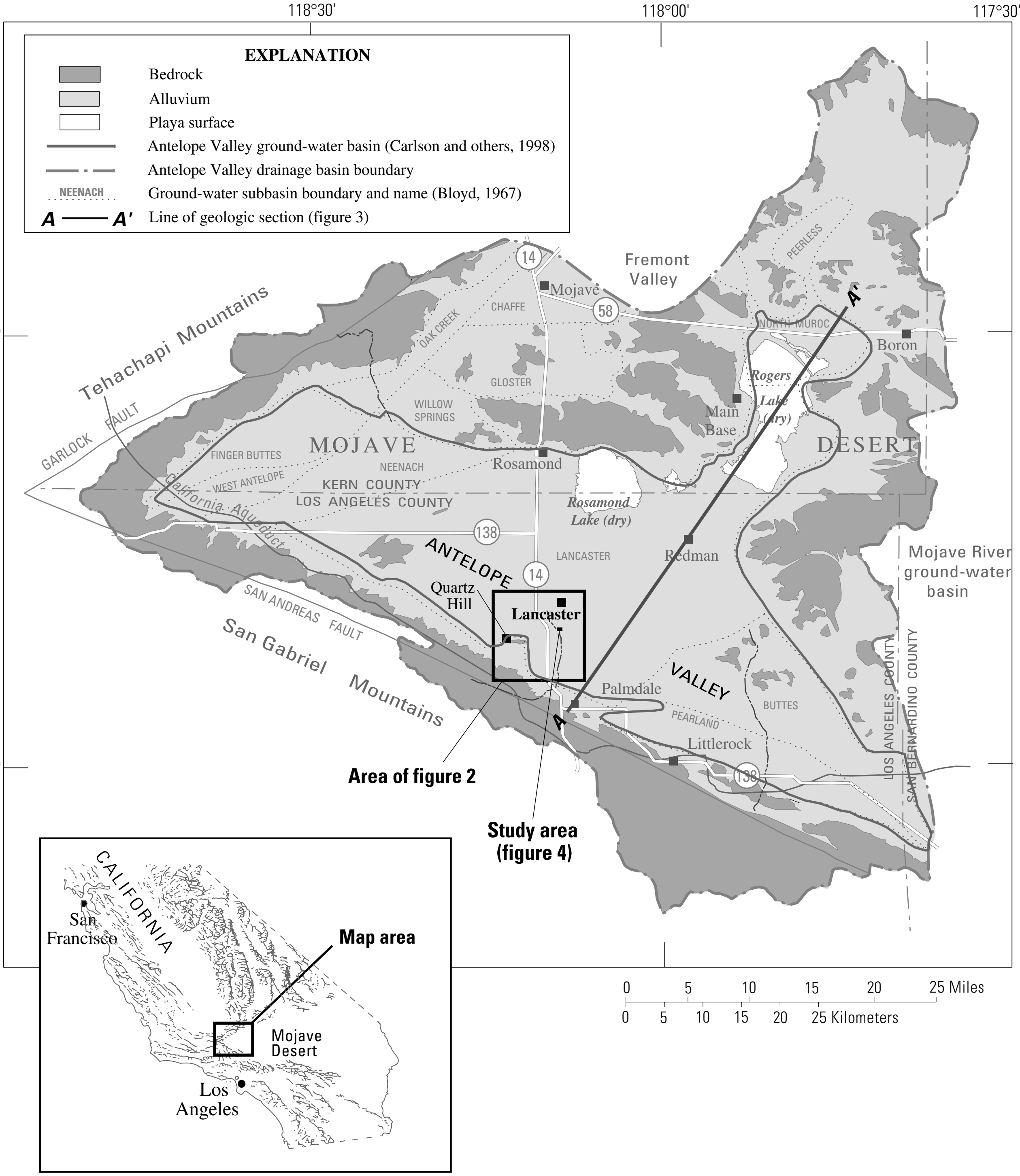

Figure 1. Location of study area and generalized surficial geology of Antelope Valley, California. (Modified from Londquist and others, 1993, figure 2).

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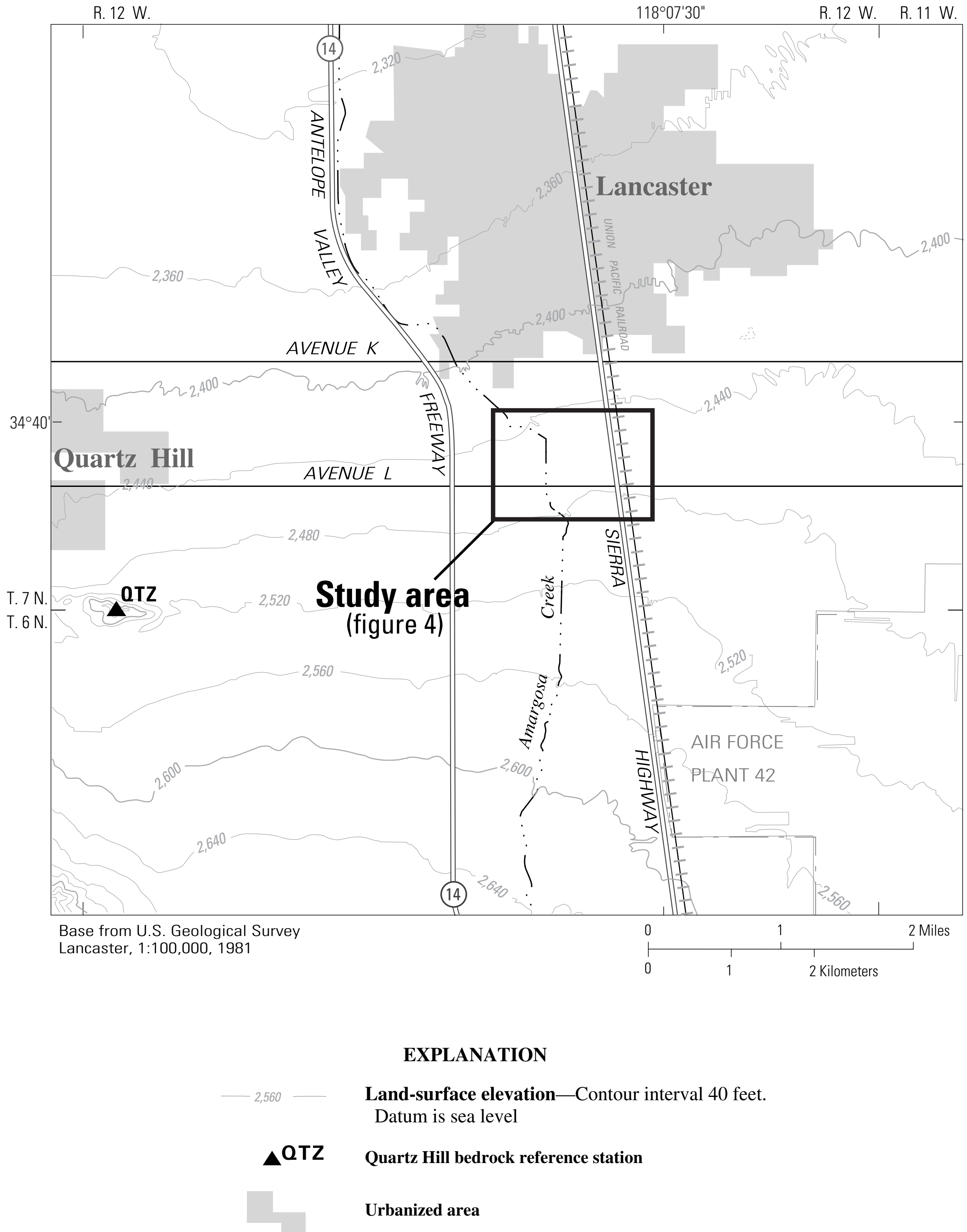

Figure 2. Location of Quartz Hill bedrock reference station and land-surface elevations in and near Lancaster, Antelope Valley, California.

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The study area is in the Lancaster subbasin of the Antelope Valley (fig. 1), which is filled with alluvial and lacustrine deposits that are locally as much as 5,000 ft thick (Brenda and others, 1960; Mabey, 1960) (fig. 3). The alluvial deposits consist of interbedded heterogeneous mixtures of silt, sand, and gravel (Dutcher and Worts, 1963; Bloyd, 1967); the lacustrine deposits primarily consist of thick layers of clay, interbedded with thinner sand and silty sand layers (Dibblee, 1967). Stratigraphic, hydrologic, and water-quality data were used to divide the deposits into three aquifers: an upper, a middle, and a lower aquifer (Leighton and Phillips, 2003). At the injection, storage, and recovery site, the upper aquifer extends from the water table to a depth of about 510 ft below land surface, the middle aquifer extends from about 510 to about 730 ft below land surface, and the lower aquifer extends from about 870 ft below land surface to the bedrock (fig. 3). Ground-water flow in the upper aquifer is unconfined, flow in the middle aquifer is unconfined to partially confined at depth, and flow in the lower aquifer is confined by the lacustrine deposit that separates the middle and lower aquifers.

As much as 2 ft of land subsidence has occurred in or near the study area from 1930 to 1992 as a result of declining ground-water levels and associated aquifer-system compaction (Ikehara and Phillips, 1994; Galloway and others, 1998b). Measurements of land subsidence for 1993–95, made using interferometric synthetic aperture radar (InSAR) (Galloway and others, 1998c), and measurements of aquifer-system compaction at a borehole extensometer for 1990–97 (Sneed and Galloway, 2000) show that subsidence continued in Antelope Valley, including the study area, during the 1990s. The subsidence is a result of the lowered hydraulic heads and increasing effective stress in the confining unit (lacustrine clay) and the interbedded clay units or aquitards (Carlson and Phillips, 1998).

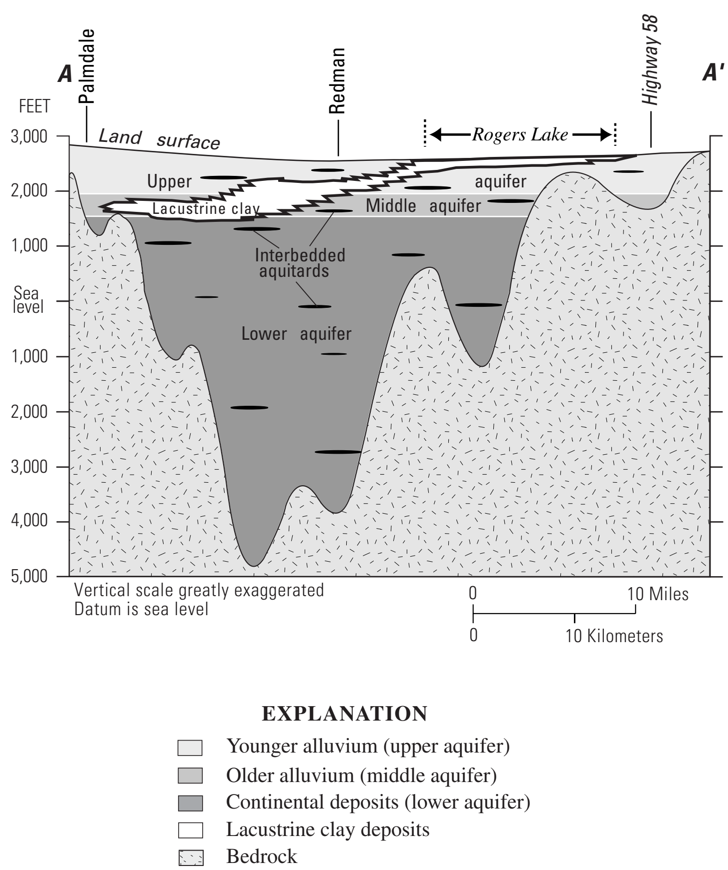

Figure 3. Generalized geologic section showing relation of lacustrine deposits to younger and older alluvium and aquifers, Antelope Valley, California. (Modified from Metzger and others, 2002). Line of section is shown on figure 1.

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Description of Injection Wells

For all three cycles of the injection, storage, and recovery tests, the water used for injection into the wells was imported from the SWP. For the cycle 2 injection test, about 1,050 acre-ft of SWP water was injected at a rate of 750 gal/min into each of two existing production (injection) wells between November 12, 1996, and April 17, 1997. These two wells (7N/12W-27P2 and 27P3), located just north of Avenue L and about 0.5 mi west of Sierra Highway (fig. 4), penetrate the upper and middle aquifers and are screened from 282 to 717 ft and 280 to 710 ft below land surface, respectively (figs. 5 and 6). A well-bore velocity log made for well 7N/12W-27P2 under pumping conditions indicates that about 90 percent of the water pumped (1,350 gal/min) was from the upper aquifer and about 10 percent (150 gal/min) was from the middle aquifer.

Previous Microgravity Studies

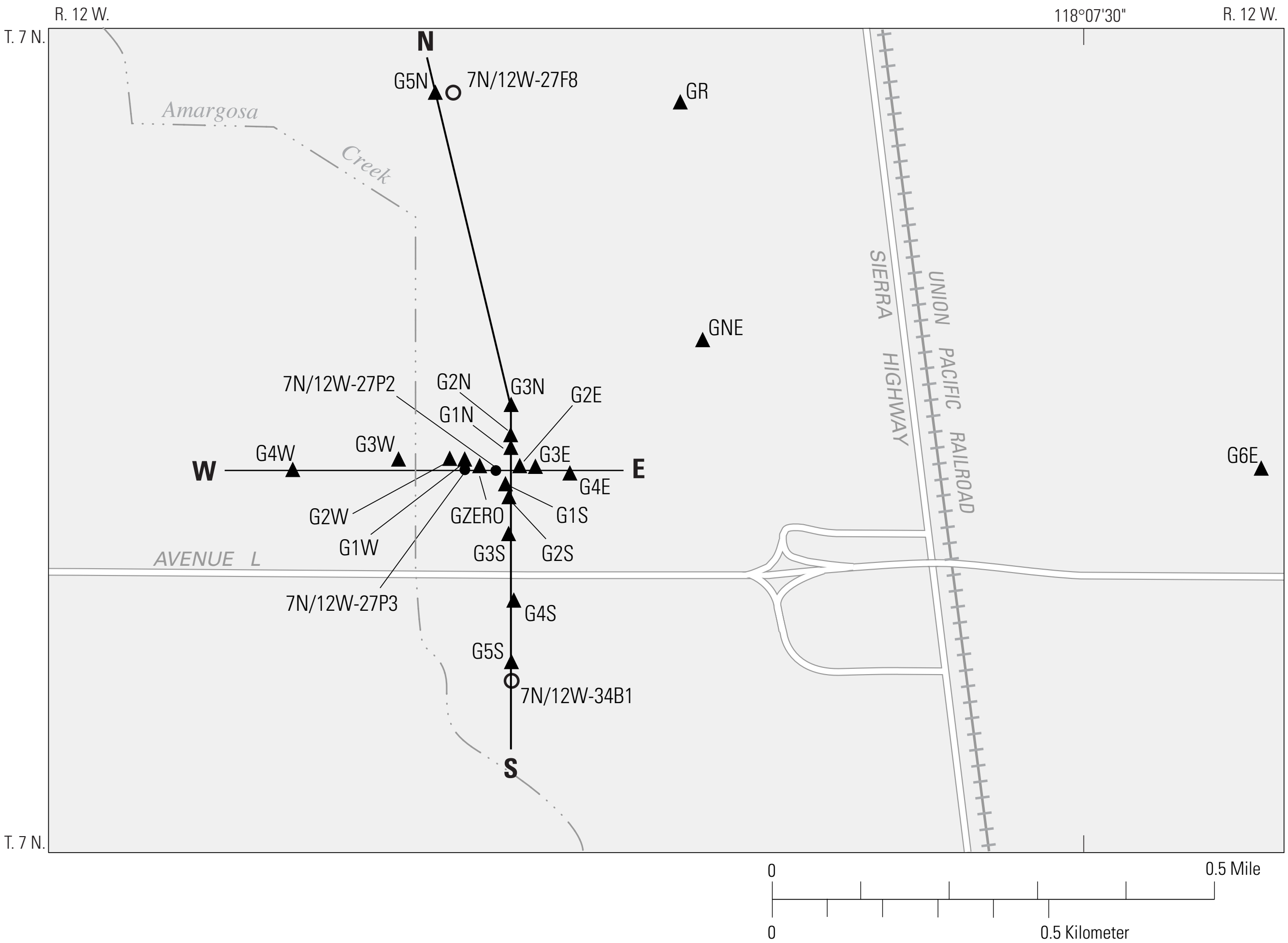
Microgravity techniques were used during previous investigations to estimate specific yield and water-level changes, although not for an injection scenario. Montgomery (1971) estimated the specific yield for an unconfined aquifer by correlating gravity and water-level variations. Pool and Hatch (1991) measured gravity changes caused by the mounding of ground water beneath an artificial recharge pond; their study most resembles this investigation. More recently, Pool and Eychaner (1995) used mircogravity surveys to determine aquifer-storage change and specific yield. Lines (1996) used microgravity surveys and water-level changes to estimate the specific yield of the flood-plain aquifer at ten sites along the Mojave River.

Microgravity Surveys

The gravity-station network consisted of 20 permanent gravity stations within 1 mi of the injection site (fig. 4). The gravity stations were areally distributed to measure the anticipated shape of the ground-water mounding around the injection wells. Temporal, or time-series, microgravity surveys were conducted at the gravity-station network to measure small changes in gravitational acceleration (also referred to as gravity) caused by subsurface changes in mass. In an injection scenario, mass, in the form of water, is added to the aquifer and the associated change in gravity is measured with a portable gravity meter. A microgravity survey was conducted prior to injection to establish baseline gravity values for the gravity-station network. Subsequent surveys were conducted to monitor the accumulation of mass and determine the areal extent of the anomalous mass with time.

In an unconfined aquifer, injected water that resaturates the alluvium causes a net increase in mass proportional to the volume of water that fills previously unsaturated pore spaces. As injection continues, a mound of water, henceforth referred to as the “mound” or “injection mound,” forms in the aquifer. Conceptually, this mound is a mirror image of the cone of depression that would form in the same aquifer material under the same rate of withdrawal as that of the injection. The mound is highest beneath the injection wells and flattens exponentially with increasing radial distance. The girth and the height of the mound increase with sustained injection until a regional static equilibrium is achieved.

In a confined aquifer, injected water will result in an increase in hydraulic head over a large area because of the low storativity typical of a saturated confined aquifer (0.005 to 0.0005; Freeze and Cherry, 1979). Temporal microgravity surveys cannot be used to monitor the change in hydraulic head in a confined aquifer because even a large increase in hydraulic head represents only a slight increase in mass beneath an individual gravity station due to the low storativity. The increases in hydraulic head, or pore fluid pressure, can cause some expansion of the aquifer system owing to the compressibility of the granular skeleton of the aquifer, and this expansion results in millimeter-to-centimeter-scale increases in land-surface elevation that can be detected by microgravity measurements and differential leveling.



EXPLANATION

W —— E	Line of profile section (shown in figures 7, 10, 11, 12, and 13)
▲G4S	Gravity station and identifier
○7N/12W-34B1	Monitoring well and identifier
●7N/12W-27P2	Injection well and identifier

Figure 4. Location of gravity stations, monitoring wells, and injection wells and of south-to-north and west-to-east profiles, Lancaster, Antelope Valley, California.

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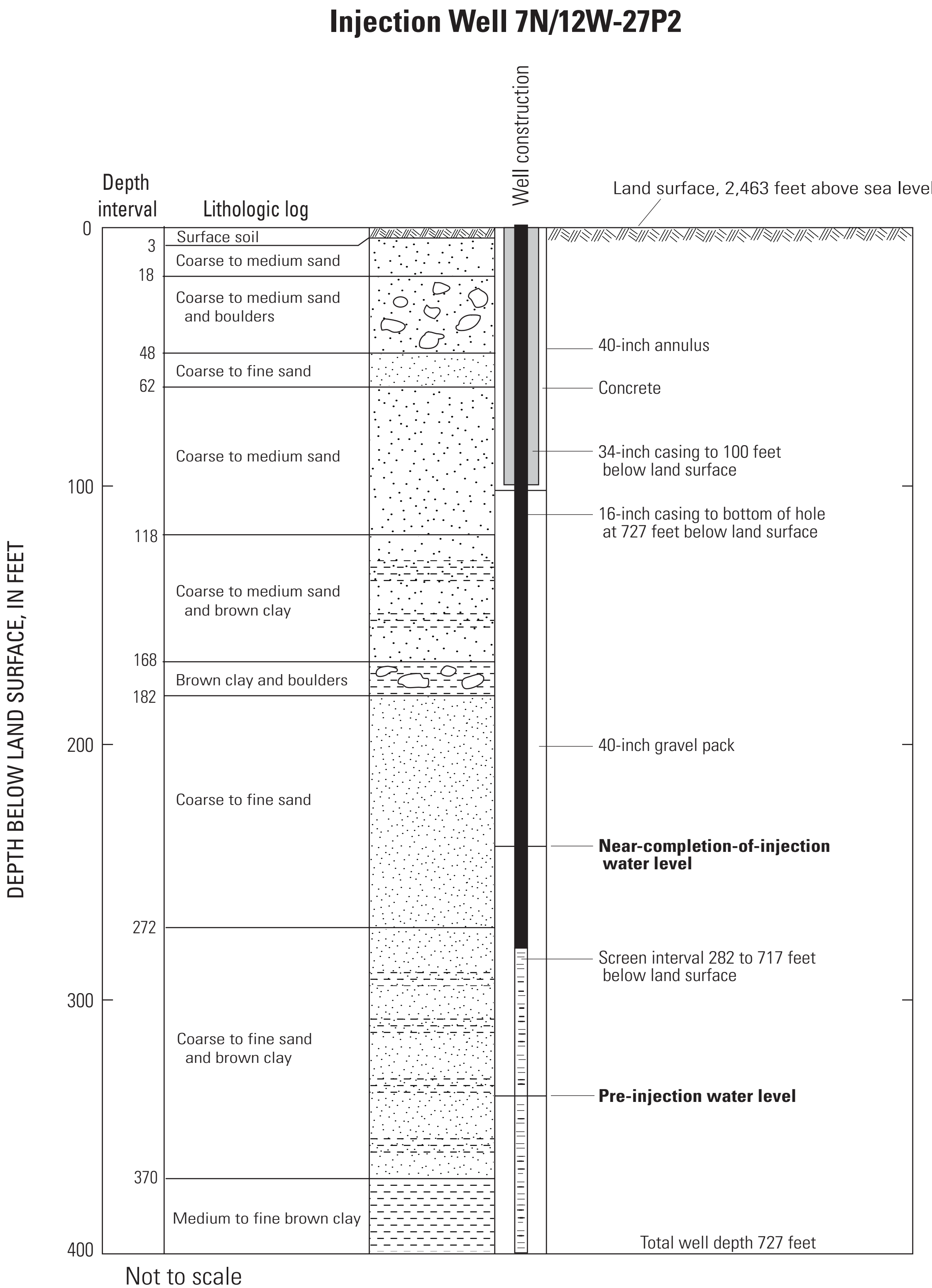

Figure 5. Lithologic log and well-construction diagram for injection well 7N/12W-27P2 in Lancaster, Antelope Valley, California.

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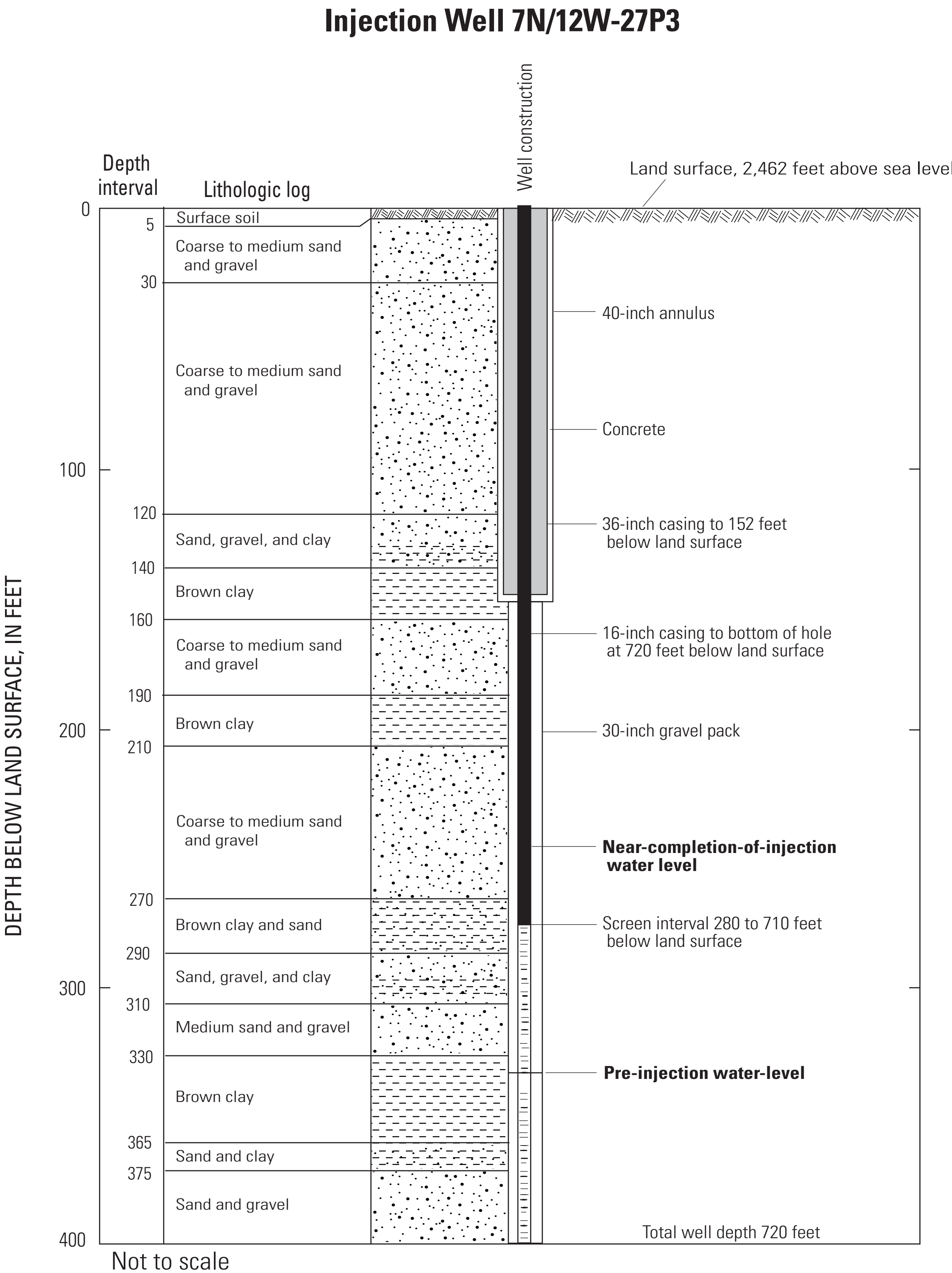

Figure 6. Lithologic log and well-construction diagram for injection well 7N/12W-27P3 in Lancaster, Antelope Valley, California.

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Table 1. Data from pre-injection, mid-injection, and near-completion-of-injection surveys for gravity stations 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 global positioning system (GPS) in 1996–97; mean difference in gravity relative to Quartz Hill (3.6 miles from injection site); elevations referenced to the National Geodetic Vertical Datum of 1929 (NGVD29) and measured by leveling to second-order standards of accuracy; elevations for the pre-injection survey measured November 4–13, 1996, and for the near-completion-of-injection, on April 9, 1997, unless indicated otherwise (see footnotes); gravity differences corrected for station elevation changes are rounded to the nearest microgal. mGal, milligal; µGal, microgal; ft, foot; m, meter; mm, millimeter; $\bar{x}$, mean; <, less than; —, no data]

Gravity station	Latitude	Longitude	Pre-injection survey (November 5–9, 1996)				Mid-injection survey (January 29–February 1, 1997)		Change in gravity from previous survey (µGal)
			Mean difference in gravity (mGal)	Standard deviation (µGal)	Elevation (ft)	Elevation (m)	Mean difference in gravity (mGal)	Standard deviation (µGal)	
GR	34°40′05″	118°08′09″	–6.098	5.3	2,445.648	745.4336	–6.097	1.8	1
G5N	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
G4W	34°39′43″	118°08′36″	–2.609	4.6	2,454.687	[1]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	[1]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	[1]749.8981	—	—	—
				$\bar{x}$ = 4.2				$\bar{x}$ = 3.6	
QTZ[2]	34°38′43″	118°12′01″			2,638.7	[3]804.3			

See footnotes at end of table.

Table 1. Data from pre-injection, mid-injection, and near-completion-of injection surveys for gravity stations at Lancaster, Antelope Valley, California, November 1996 through April 1997—Continued

Gravity station	Near-completion-of-injection (April 5–12, 1997)				Change in gravity from previous survey (μGal)	Change from pre-injection		Change in elevation effect (μGal)	Gravity difference corrected for station elevation change (μGal)
	Mean difference in gravity (mGal)	Standard deviation (μGal)	Elevation (ft)	Elevation (m)		Microgravity (μGal)	Elevation (mm)		
GR	–6.095	7.4	—	—	2	3	—	([4])	3
G5N	–4.767	4.3	2,441.614	744.2038	3	7	2.4	1	8
G3N	–4.646	1.3	2,459.700	749.7166	13	38	.8	<1	38
G2N	–4.592	4.1	2,461.430	750.2440	14	41	.4	<1	41
G1N	–4.562	2.5	2,462.124	750.4554	18	49	.3	<1	49
G4W	–2.572	3.5	—	—	5	37	—	([4])	37
G3W	–3.599	4.9	2,459.407	749.6272	11	49	.4	<1	49
G2W	–3.982	4.6	2,460.467	749.9504	-2	32	–.7	<1	32
G1W	–4.157	1.8	2,461.484	750.2602	5	39	–1.0	<1	39
GZERO	–4.254	3.5	2,461.619	750.3014	12	44	–1.1	<1	44
G5S	–4.769	3.1	—	—	10	30	—	([4])	30
G4S	–4.653	4.8	2,469.983	752.8509	5	24	.8	<1	24
G3S	–4.510	2.5	2,465.879	751.6000	4	30	–.4	<1	30
G2S	–4.563	4.7	2,464.708	751.2431	9	44	–.2	<1	44
G1S	–4.507	2.5	2,463.881	750.9908	11	66	–.3	<1	66
G6E	–9.519	1.4	—	—	—	9	—	([4])	9
G4E	–5.218	1.9	2,465.966	751.6265	19	32	.8	<1	32
G3E	–4.887	0.6	2,464.279	751.1123	19	40	.6	<1	40
G2E	–4.715	5.0	2,463.550	750.8901	1	38	.1	<1	38
GNE	–6.077	3.8	—	—	—	9	—	([4])	9
		$\bar{x} = 3.4$							

[1]Elevation measured March 26–28, 1996.
[2]Bedrock promontory used as a stable gravity reference.
[3]Determined by GPS in 1996.
[4]Where vertical control is missing, the free air effect was assumed to be zero.

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A microgravity survey consists of two loops of measurements that begin and end at a reference station. For this study, two reference stations were established—one at Quartz Hill (QTZ) about 3.5 mi west-southwest of the injection site and one (GR) within the study area (figs. 2 and 4). Quartz Hill, a crystalline bedrock promontory, was used as a stable gravity reference. The GR reference station was established to eliminate the travel time between the QTZ reference station and the study area. GR is located about 0.5 mi upgradient from the injection site where water-table change and associated changes in mass were expected to be minimal.

Three microgravity surveys (pre-injection, mid-injection, and near-completion-of-injection) were done for the cycle 2 injection test (table 1). Gravity was measured three times at the GR reference station during each survey to evaluate instrument drift during the survey and twice at each gravity station to assess the repeatability and accuracy of the measured differences in gravity. The mean difference in gravity and the standard deviation for each station (table 1) were calculated from two measurements made within 2 to 3 hours of each other. A thorough discussion of the methods of data collection and of the sources of survey error is given by Metzger and others (2002, appendixes A, B, and C). All values of gravity are relative to the QTZ bedrock reference station.

For each of the surveys, the first step consisted of determining the difference in gravity between the QTZ reference station, where mass changes were expected to be negligible, and the GR reference station. The variation in the surveyed mean difference in gravity for the GR reference station was 3 μGal, ranging from –6.098 mGal in the pre-injection survey to –6.095 mGal in the near-completion survey (table 1). Once the mean difference in gravity between the QTZ and GR reference stations was established for each survey period, surveys relative to the GR station were made. The total difference in gravity between the QTZ reference station and the gravity stations in the study area was determined by adding the difference in gravity between the QTZ and the GR reference stations to the difference between the GR station and other stations in the study area. Absolute values of gravity were not determined, but absolute values of gravity for this part of Antelope Valley are about 979,500 mGal (Hanna and Sikora, 1973).

Changes in elevation at a gravity station can affect a measurement of gravity because of the strong vertical gradient of gravity, 308.6 μGal/m (Dobrin, 1960, p. 189). Because gravity measurements are reported to an accuracy of 1 μGal, gravity-station elevation changes greater than 1.6 mm were corrected for a change in the elevation of the gravity station. For example, an increase in elevation of 0.0016 m (1.6 mm) at a station will decrease the measured gravity value at that station by about 0.5 μGal and a decrease in elevation of 0.0016 m will increase the measured gravity value at the gravity station by about 0.5 μGal. For this study, differential leveling done to second-order results (Bossler, 1984) was used to detect the vertical changes at the gravity stations (table 1). With the exception of gravity station G5N, all the gravity stations had elevation changes less than or equal to 1.6 mm and no correction to the measured difference in gravity was required (table 1).The maximum elevation change was detected at gravity station G5N (+2.4 mm) between the pre-injection and the near-completion-of-injection surveys. A change of 0.0024 m in elevation at the G5N station resulted in a change in gravity of 0.7 μGal. The positive elevation change means that the gravity station is further from the injection mound mass and, therefore, the measured difference in gravity is deficient (Nettleton, 1976, p. 19). To correct the measured difference in gravity (7 μGal) for the positive elevation change, 0.7 μGal was added to the measured difference, giving a change in gravity of 7.7 μGal for station G5N. Because only one gravity station required an elevation-change correction, the measured changes in gravity during the injection cycle cannot be the result of gravity station elevation changes.

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The maximum positive elevation change between the pre-injection and the near-completion-of-injection surveys was expected to be near the injection wells, where aquifer deformation owing to increased pore-fluid pressure in the confined units may cause expansion of the granular skeleton of the aquifer. However, the maximum positive elevation change was at the G5N gravity station, which is about 2,300 ft north of the injection wells. This spatial discrepancy may be related to the variability in the poroelastic properties of the aquifer material. Time-series leveling data for the study area (Metzger and others, 2002; Phillips and others, 2003) and InSAR data (Galloway and others, 1998c) indicate that the elastic skeletal specific storage (the component of storage associated with the elastic deformation of aquifer materials) is greater at the northern end of the study area than in the area of the injection wells, which may account for the larger elevation changes at G5N.

DETERMINATION OF SPECIFIC YIELD

Gravity and ground-water levels were measured simultaneously at monitoring well 7N/12W-34B1 (fig. 4) to calculate specific yield for the unconfined (water table) aquifer for the vertical interval of water-level change. Specific yield is the volume of water that drains by gravity or that resaturates under hydrostatic conditions for a unit volume of aquifer material and is expressed as a dimensionless fraction or percentage.

A change in gravity is related to a change in mass, which is attributed to the change in the volume of water occupying pore space in the unconfined aquifer and can be calculated by

$$\Delta g / 12.77 = \Delta mass \ (Dobrin, 1960), \qquad (1)$$

where

- Δg is the measured change in gravity, in microgals,
- 12.77 is the mass equivalent of 1 ft of water, assuming a slab geometry of infinite extent, in microgals, and
- Δ mass is the change in mass at a gravity station, in equivalent feet of water.

Specific yield (S_y) was determined by dividing the change in mass by the measured water-level change (Δ water level)

$S_y = \Delta$ mass/Δ water level (Pool and Eychaner, 1995). (2)

Once the specific yield is known and the change in mass is known, the change in water level can be calculated by solving for Δ water level using equation 2.

For a 3-week period prior to cycle 2 injection, wells operated by the Los Angeles County Department of Public Works within 1 mi of the injection site were not pumped to allow water levels to approach static equilibrium, or recover (Metzger and others, 2002). During this period, water levels were monitored at well 7N/12W-34B1, which is 30 ft south of gravity station G5S (fig. 4). Near the end of this recovery period (November 7, 1996), the mean difference in gravity at G5S relative to the QTZ reference station was –4.799 mGal (1 standard deviation = 3.1 μGal) (table 1) and the water level at well 7N/12W-34B1 was 351.8 ft below land surface (table 2). Measurements were repeated on April 10 and 11, 1997, near the end of the injection period. The mean gravity difference was –4.769 mGal (1 standard deviation = 3.1 μGal) and the ground-water level was 334.0 ft below land surface, yielding changes of 30 μGal and 17.8 ft, respectively. Substituting 30 μGal for the measured change in gravity in equation 1 yields an increase in mass equivalent to 2.35 feet of water at well 7N/12W-34B1. Substituting 2.35 ft of water for change in mass and 17.8 ft for water-level change in equation 2 results in a specific yield of 0.13.

The calculated specific yield of 0.13 for the aquifer in the study area is in general agreement with the values of 0.10 to 0.15 estimated by Durbin (1978) for this part of the Antelope Valley. Durbin estimated the specific yield using lithologic well logs and then correlated the lithologic data with data from laboratory tests by Bloyd (1967), which were done on similar materials collected from Antelope Valley. The specific yield using microgravity measurements (0.13) was used in two models being developed for the study area, a regional-scale (Leighton and Phillips, 2003) and a subregional-scale numerical model (Phillips and others, 2003).

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EFFECT OF INJECTION MOUND ON THE CALCULATED SPECIFIC YIELD

The irregular geometry of the injection mound may affect the measured vertical component of gravity at the G5S station and hence the calculated specific yield. The value for the mass equivalent of 1 foot of water, 12.77 μGal (equation 1) (Dobrin, 1960, p. 175), assumes a slab geometry of infinite extent: however, the geometry of the injection mound is better depicted as a series of stacked disks of finite diameter, each having a smaller diameter than the disk below it. The discrepancy between the slab geometry and the geometry of the injection mound casts doubts as to whether equation 1 can be used to estimate the change in mass in equivalent feet of water.

A commercially available two-dimensional gravity model (GravModeler) was used to assess the gravitational effect of the injection mound on the gravity measurement at the G5S station.The model is based on the line integral approach of Talwani and others (1959), who derived expressions for the vertical and horizontal components of the gravitational acceleration for a two-dimensional polygon of arbitrary shape. GravModeler computes the gravity response at the earth's surface across the model width due to a two-dimensional buried mass or polygon. The polygon is defined in terms of density, depth, and cross sectional geometry. The two-dimensional computation means that the user-defined polygons are assumed to be infinite in extent into and out of the model profile. Polygons that intersect the right and left model boundaries also are assumed to be infinite in extent. GravModeler computes the gravity response based on the density contrast between the polygon in question (injection mound) and the background density (aquifer material). The modeled density contrast between saturated and unsaturated aquifer material is proportional to the porosity or specific yield (Nettleton, 1976, p. 245). Because the density of water is 1 g/cm^3 and the calculated specific yield was 0.13, the density contrast of the injected mound was simulated as 0.13 g/cm^3. The depth to the bottom of the injection mound was based on the pre-injection water-level elevation measured in three wells along the south to north profile (fig. 7*A*; table 2). The model width (5,000 ft) was chosen such that the infinitely projected polygons at the model boundaries would have a relatively small thickness. Therefore, the computed gravity response resulting from this boundary assumption would be negligible near G5S. The cross sectional geometries of the various injection mounds (fig. 7*A*) were entered into GravModeler using a graphical user interface.

The injection mound geometries were determined using the USGS three-dimensional ground-water flow model MODFLOW developed by McDonald and Harbaugh (1988). The ground-water flow model was used to simulate the upper part of the aquifer system in the study area during the injection test. The simulation was done for transient conditions using 15 stress periods of 10 days each. The lateral model boundaries were about 7,500 ft from the injection wells (fig. 8). A constant southward hydraulic gradient of 0.0017 was specified on the basis of measured water levels. Cell sizes were varied laterally, increasing from 20 ft^2 at the injection wells to more than 300 ft^2 at the outer margins of the modeled area. Cell thickness initially was 200 ft for a single-layer model, but varied with water-table change. The thickness of the cells corresponds to that determined from regional and local investigations of the aquifer system (Leighton and Phillips, 2003) and is considered to represent the unconfined part of the aquifer system. The only stress represented in the ground-water flow model was injection, which was specified at a constant rate of 675 gal/min (90 percent of the total injection rate) for each of the two injection wells (7N/12W-27P2 and 27P3). The model domain was assumed to have a specific yield of 0.13 (the gravity-derived value). Five model simulations were run with different hydraulic conductivity values (8, 10, 12, 15, and 18 ft/d), which are within the range of the values estimated from results of aquifer-test analyses and of the simulations of the study area. The hydraulic conductivity value was assumed to be constant over the model area for each simulation (figs. 7 and 8).

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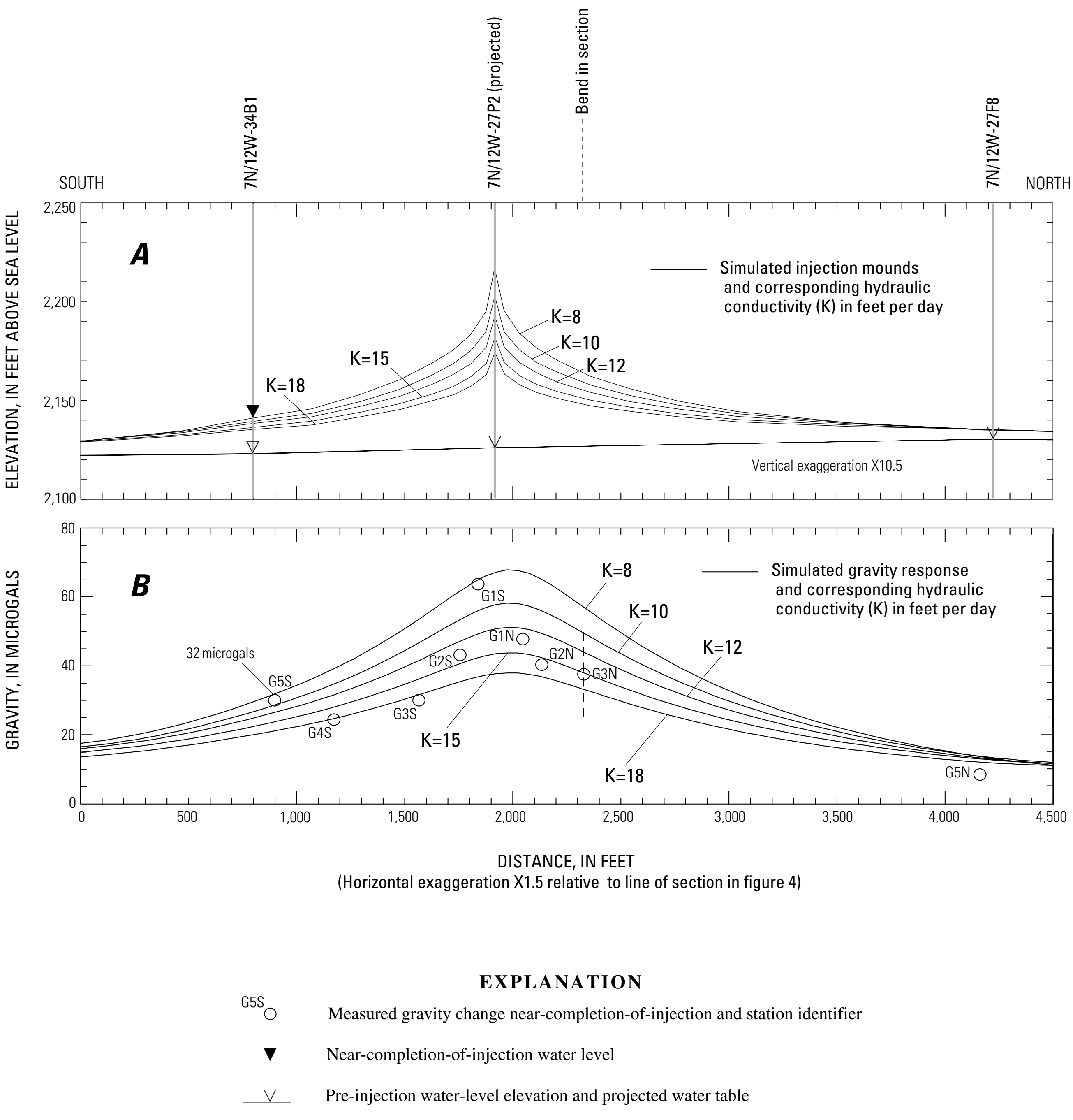

Figure 7. South-to-north profile showing (***A***) simulated injection mound geometries and corresponding hydraulic conductivity, and (***B***) the simulated two-dimensional gravity response to various injection mound geometries, and measured gravity changes at the near-completion-of-injection survey at Lancaster, Antelope Valley, California.

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Table 2. Selected ground-water-level measurements for the pre-injection and near-completion-of-injection surveys at Lancaster, Antelope Valley, California, November 1996 through April 1997

Injection period	7N/12W-34B1			7N/12W-27P2			7N/12W-27P3			7N/12W-27F8		
	Date	Water-level depth below land surface (feet)	Water-level elevation (feet)	Date	Water-level depth below land surface (feet)	Water-level elevation (feet)	Date	Water-level depth below land surface (feet)	Water-level elevation (feet)	Date	Water-level depth below land surface (feet)	Water-level elevation (feet)
Pre-injection water-level measurements	11/07/96	351.8	2,123	11/12/96	337.3	2,126	11/12/96	337.3	2,125	11/09/96	311.4	2,130.2
Near-completion water-level measurements	04/10/97	334.0	2,141	04/14/97	238.7	2,224	04/17/97	236.1	2,226	04/16/97	300.6	2,141.0

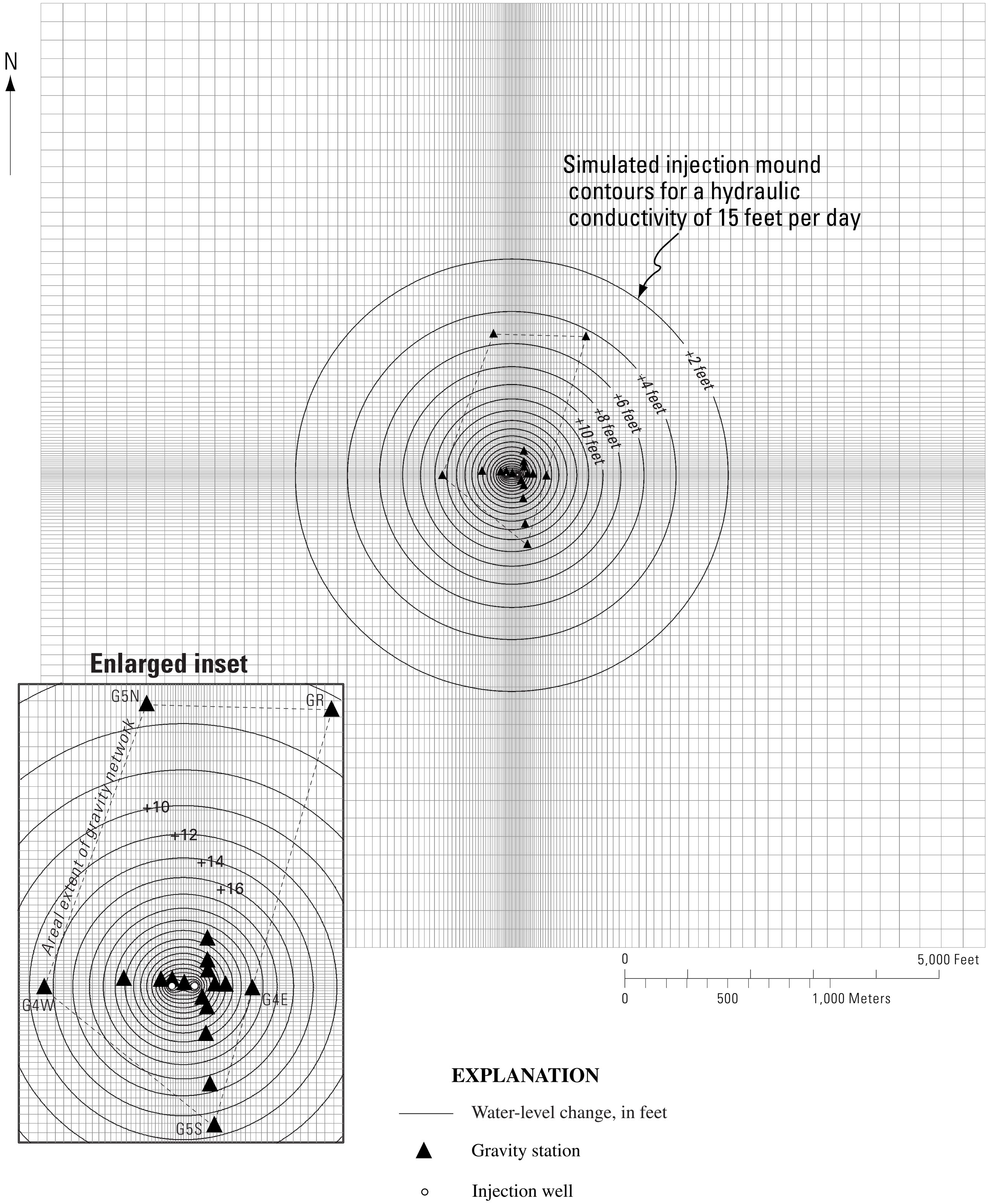

Figure 8. Model grid and simulated injection mound contours and areal extent of the gravity station network in Lancaster, Antelope Valley, California.

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Figure 7*B* shows the gravitational response at the G5S gravity station to various simulated injection mound geometries. Results of the simulations show that lower hydraulic conductivity values resulted in a higher injection mound than did the higher hydraulic conductivity values (fig. 7). Thus, the injection mound simulated with the lowest hydraulic conductivity value (8 ft/d) yielded the greatest gravitational response (32 μGal) at the G5S gravity station, 2 μGal greater than the measured change of 30 μGal at the G5S gravity station for the near-completion-of-injection survey (table 1).

As previously mentioned, the injection mound can be visualized as a stack of disks, each having a smaller diameter than the disk below it, or as a flattened cone. The two-dimensional gravity model, however, calculated the volume of the mound as an infinite ridge, rather than as a cone, with a cross-sectional geometry equivalent to that shown on the south-to-north profiles in figure 7*A*. The larger volume resulting from the infinite ridge caused an overestimation of the gravity response, which was greatest at the ridge crest and decayed with distance from the injection wells. Even if the 2-μGal gravitational effect of the largest simulated injection mound is not reduced to compensate for the overestimated volume of the infinite ridge, it is small relative to the measurement error of 6.2 μGal at the G5S gravity station (the sum of the standard deviations of the measured mean difference in gravity from the pre-injection and near-completion-of-injection surveys; (table 1). Therefore, the irregular injection mound geometry is considered to have had a negligible effect on the measured gravity at the G5S station and the specific yield calculation. If the injection mound had been much larger or if the gravity station had been closer to the injection mound, the mass of the injection mound would have had a more significant effect on the measured gravity.

GRAVITY-DERIVED WATER-LEVEL CHANGES

Ground-water-level changes were estimated at each gravity station using the gravity-derived specific yield (0.13) and gravity changes measured during the near-completion-of-injection survey (table 1). The relation among water-level change, specific yield, and change in gravity is shown in figure 9.

The gravity-derived water-level changes and the simulated water levels along the south-to-north and the west-to-east profiles are shown in figures 10 and 11. The gravity-derived water levels reasonably match the simulated injection mounds along the south-to-north profile for a range of hydraulic conductivities (8 to 18 ft/d; fig. 10), except near the injection wells. The difference between the measured water-level change at well 7N/12W-34B1 and the simulated water-level changes varies from 0.3 ft for a hydraulic conductivity of 8 ft/d to –5.6 ft for a hydraulic conductivity of 18 ft/d (fig. 10).

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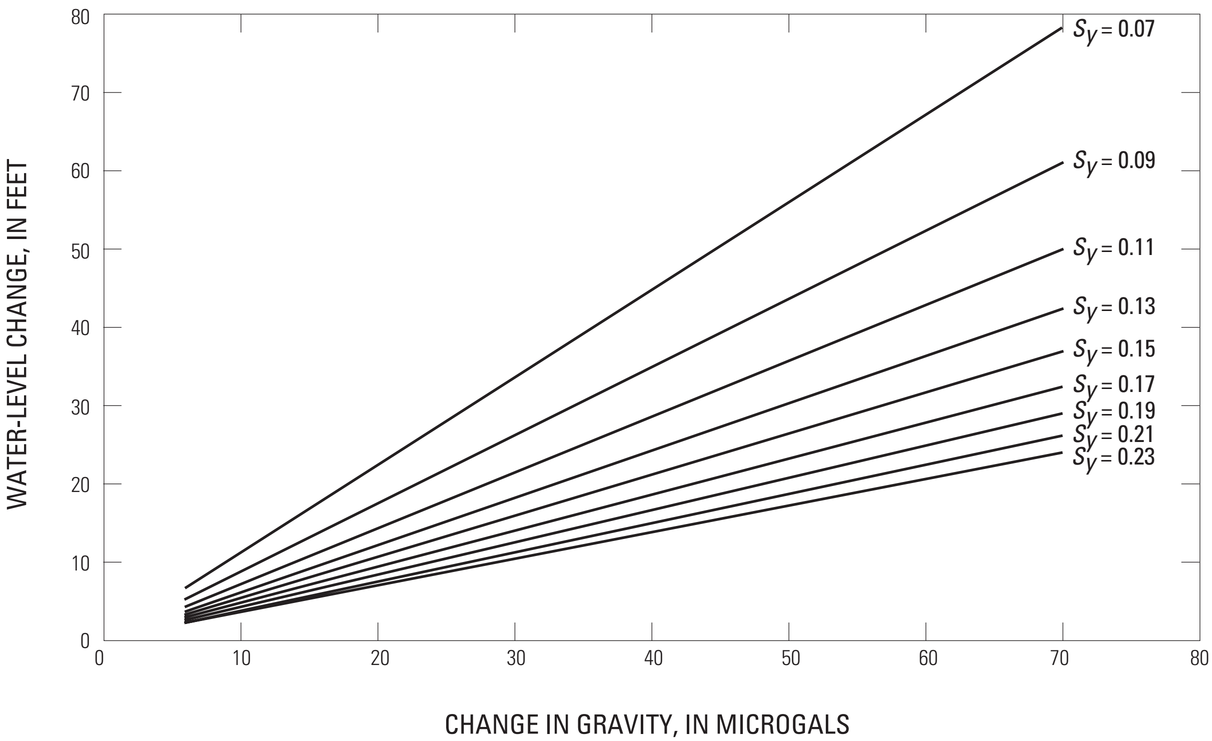

Figure 9. Relation among gravity change, specific yield, and water-level change assuming a slab geometry of infinite extent.

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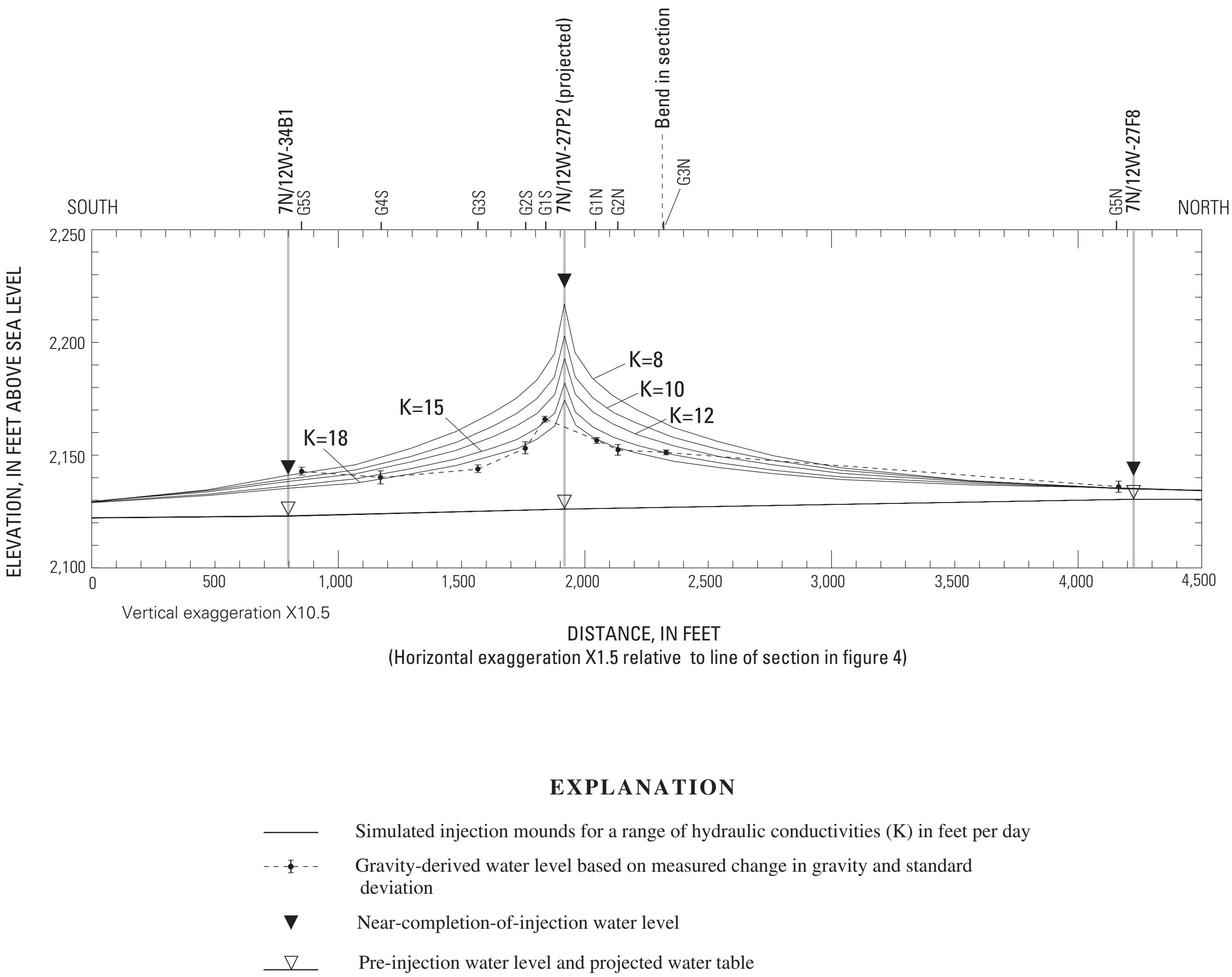

Figure 10. Gravity-derived and measured water levels compared to simulated injection mounds for a range of hydraulic conductivities along the south-to-north profile, Lancaster, Antelope Valley, California. Location of profile shown in figure 4.

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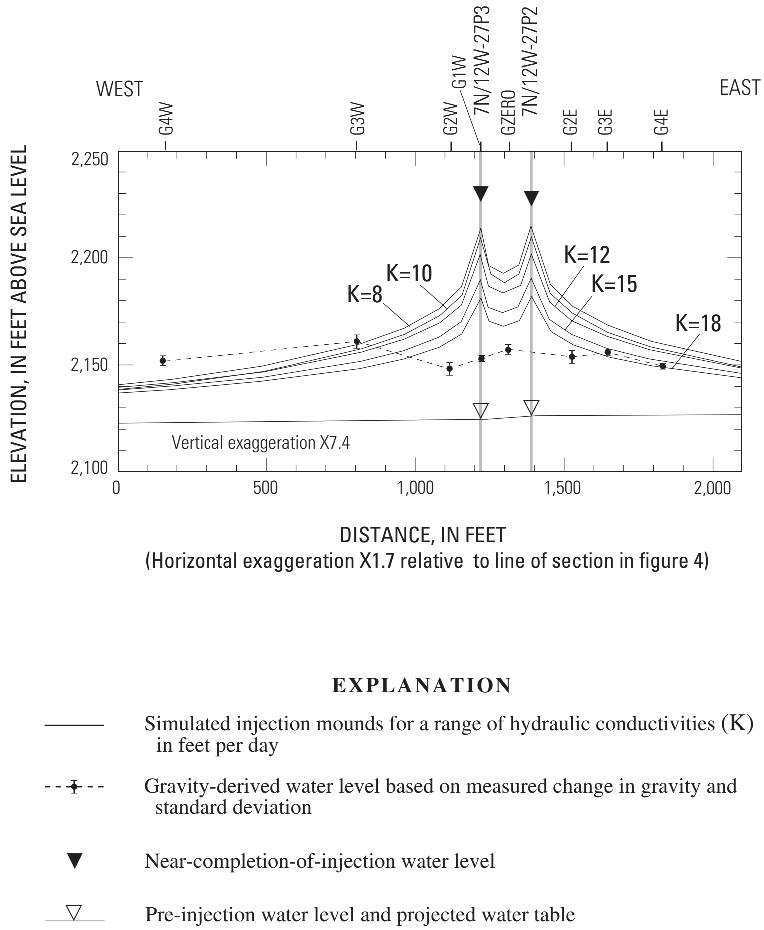

Figure 11. Gravity-derived and measured water levels compared to simulated injection mounds for a range of hydraulic conductivities along the west-to-east profile, Lancaster, Antelope Valley, California. Location of profile shown in figure 4.

The gravity-derived water levels along the west-to-east profile were within the range of the simulated water levels farthest east of the injection wells for hydraulic conductivities 15 to 18 ft/d (fig. 11), but the gravity-derived water levels at gravity stations G2E, GZERO, G1W, and G2W, which are near the injection wells, were lower than the simulated water levels. Because of the proximity of these stations to the injection wells, the changes in water levels and gravity were expected to be large. A subsequent injection test at this same site (Metzger and others, 2002) produced similar results with a distinct gravity low at the G2W station and a corresponding gravity high at the G3W station. This suggests that there are intrinsic differences in the aquifer material being resaturated beneath these stations. Possible explanations for the discrepancy between the simulated and gravity-derived water levels near the injection site may be the variability of the aquifer properties (hydraulic conductivity and specific yield) and (or) interference from environmental factors associated with the injection site (vibration from the injection wells, electromagnetic fields created from the high-voltage power supply for the injection wells, and buried water-supply pipes) that may affect gravity measurements. Additional data on the aquifer properties and the effect of these environmental factors on gravity measurements are needed to further explain these discrepancies.

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The changes in gravity (pre-injection to the mid-injection to the near-completion-of-injection) at the gravity stations along the west-to-east and south-to-north profiles are shown in figures 12 and 13. Most of the gravity change at the stations along the two profiles occurred by midway through the cycle 2 injection. On day 81 of 157 days of injection, 77 and 70 percent of the total gravity change along the west-to-east and south-to-north profiles, respectively, had occurred. Because the rate of injection was constant for the 157-day period, the large percentage of the gravity change by mid-injection suggests that the growth of the injection mound was slowing (approaching static equilibrium) and that the hydraulic response to the injection was spreading at the periphery of the mound beyond the areal extent of the gravity network (fig. 8).

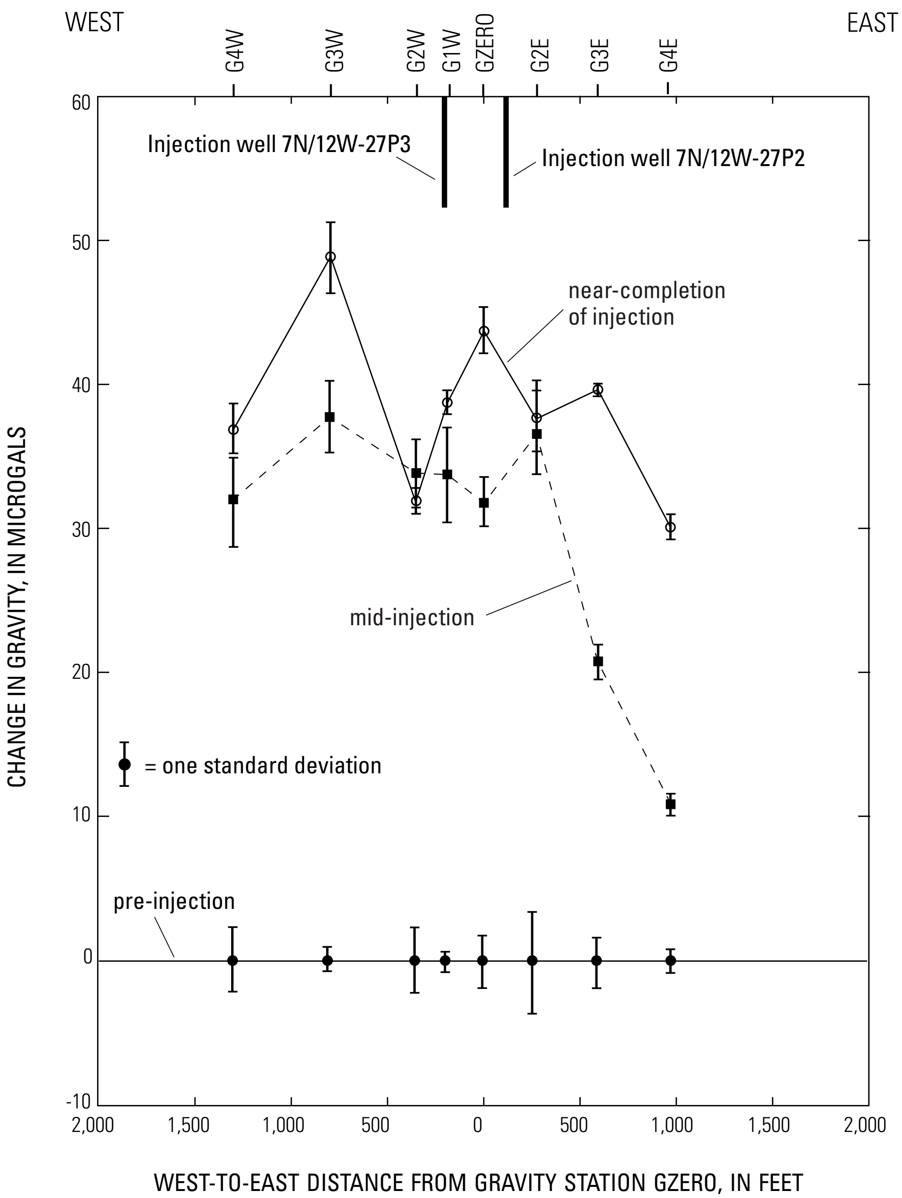

Figure 12. Change in gravity at gravity stations along the west-to-east profile, Lancaster, Antelope Valley, California. Location of profile shown in figure 4.

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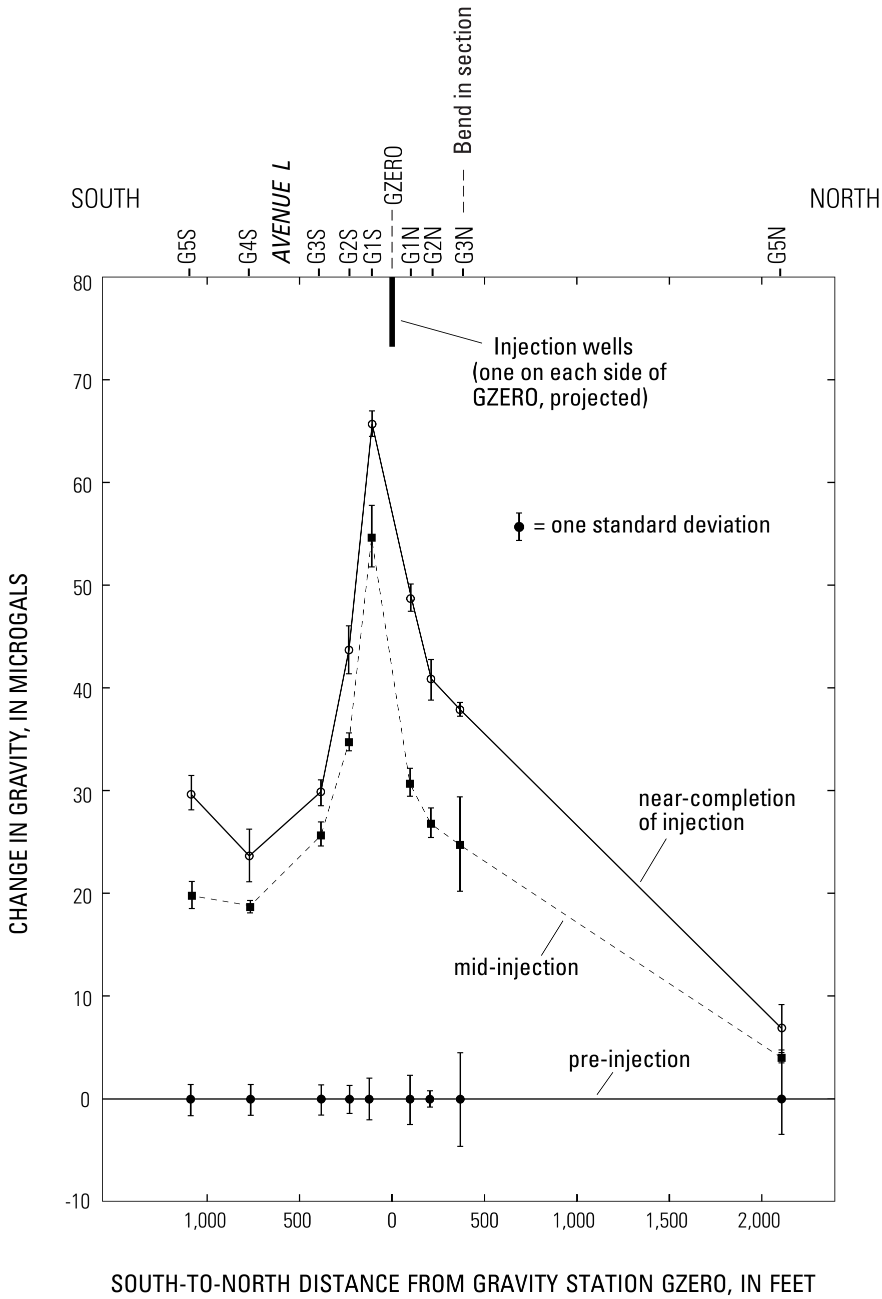

Figure 13. Change in gravity at gravity stations along the south-to-north profile, Lancaster, Antelope Valley, California. Location of profile shown in figure 4.

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COMPARISON OF GRAVITY-DERIVED ACCUMULATED MASS AND INJECTED VOLUME

Gravity changes determined from the temporal microgravity surveys were analyzed to obtain the accumulated mass within the unconfined aquifer during the cycle 2 injection period. The accumulated mass was reduced to a gravity-derived injection rate and compared with the measured injection rate to determine if the gravity changes reflect the volumetric response to injection.

As outlined by Telford and others (1976, p. 85–87), it is possible to determine the total mass of any gravity anomaly using Gauss' theorem. The expression for the anomalous mass (M) is given by

$$M = \frac{1}{2\pi\gamma}\int\int_{area} \Delta g(x, y)dxdy\,, \qquad (3)$$

where

γ is the universal gravitational constant,

Δg (x, y) is the gravity change for the surface area, and

dxdy is an infinitesimally small surface area.

The total sum of gravity change or accumulated mass can be obtained by integrating the entire gravity anomaly for a region in which it is observed. For this study, this was done by triangulating the observation points to determine an irregular triangular mesh and then integrating the gravity for each triangle by assuming a linear variation of gravity between measured values on the vertices of each triangle. The result of this integration provided the total accumulated mass produced by the anomaly.

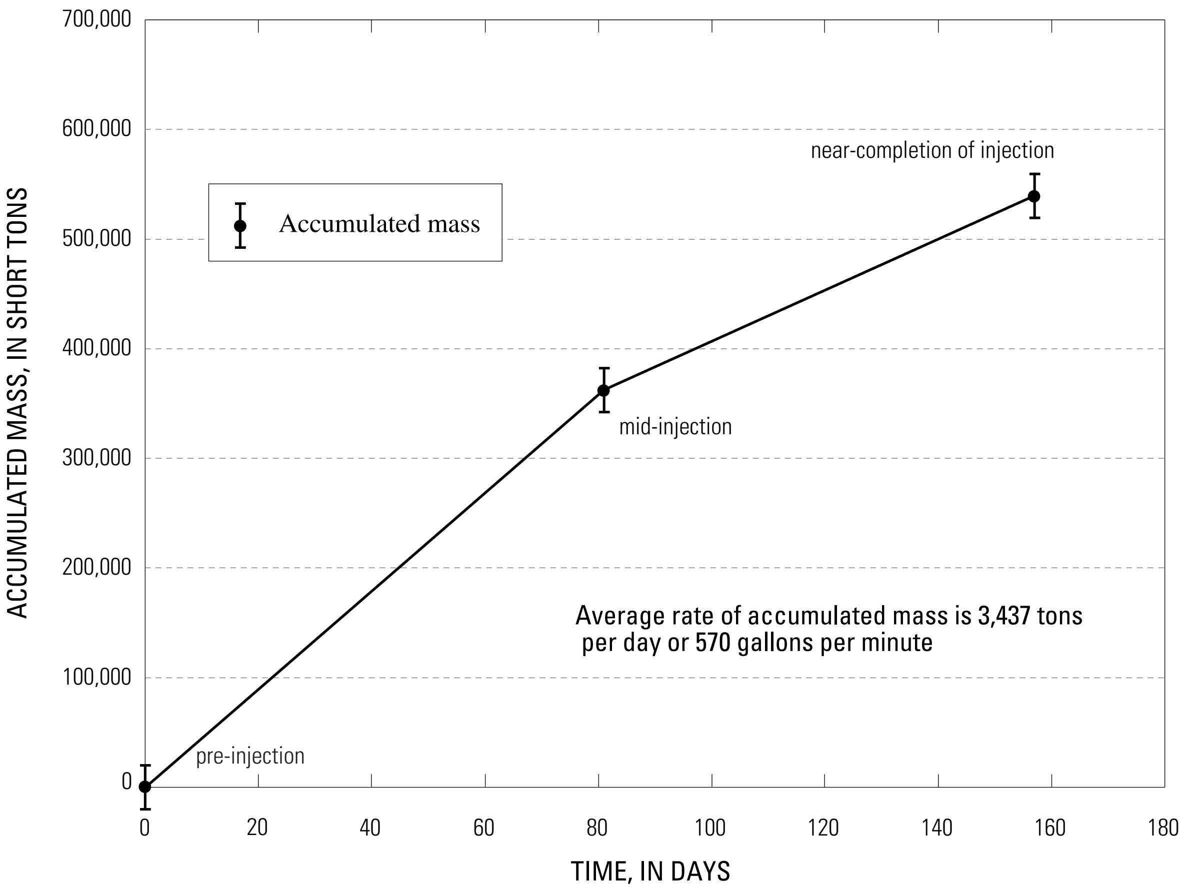

Figure 14. Accumulated mass at the pre-injection, mid-injection, and near-completion-of-injection surveys, Lancaster, Antelope Valley, California.

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The accumulated mass in terms of short tons of water is plotted with respect to time on figure 14. The average injection rate derived from the accumulated mass over the injection period (157 days) is 3,437 tons per day, or 570 gal/min; this is 42 percent of the injection rate for the upper aquifer (about 1,350 gal/min). The difference between the injection rate derived from the accumulated mass and the measured injection rate suggests that most of the injection mound was beyond the areal extent of the gravity network. The ground-water flow model results also showed that most of the area over which the water-levels changed was outside the area of the gravity network (fig.8).

DISCUSSION OF GENERAL APPLICABILITY AND LIMITATIONS OF TEMPORAL MICROGRAVITY SURVEYS

In an injection scenario, time-series microgravity surveys may be effective for determining aquifer specific yield, estimating water-table changes, and elucidating the areal extent of an injection mound. Listed below are some limitations of this geophysical technique and considerations for its successful application.

(1) At specific yield of 0.10, a 1 mm change in gravity-station elevation is the gravimetric equivalent of about 73 mm of water-level change (Pool and Eychaner, 1995). Vertical control accurate to within 1 mm is required to rule out, or compensate for, changes in elevation.

(2) Microgravity surveys cannot distinguish between water-table rise and water added to the unsaturated zone above the water table.

(3) Gravity stations used for determining specific yield should be sufficiently distant from the injection mound to minimize the effect of the irregular injection mound geometry on the measured gravity and hence the specific yield. Precursory modeling of the hydraulic and gravity responses to injection can greatly aid in determining the potential for such error, and in designing well and gravity networks if the potential error is significant.

(4) The depth to the water-table relative to the lateral extent of the water-table change can limit the application of measured gravity changes for estimating water-level changes or accumulated mass. If the depth is large relative to the lateral extent of the injection mound, the gravity signal would be distributed over a broad area of the land surface, which would cause the shape of the injection mound to be muted or indistinguishable. The ratio of the depth to the mound to the lateral extent of the mound should be much less than 1. For this study, the ratio of the depth to the mound to the simulated radius of influence is about 0.02. This ratio was adequate for using the gravity measurements to detect the shape of the injection mound.

(5) The areal extent of gravity measurements for determining water-table changes is limited by the resolution of the gravity meter used and by the aquifer properties. For example, if the minimum resolution of a particular meter is 10 μGal and the specific yield of the aquifer is 0.13, the minimum detectable water-level change is 6 ft (fig. 9). Consequently, the tapering edges of an injection mound less than 6 ft thick would be undetectable by the gravity meter.

(6) Environmental factors such as proximity to sources of vibrations (trains, trucks, and earth moving equipment), electromagnetic fields (high-voltage power lines, radio broadcasting facilities, and cell phones), buried water pipes, and earthquakes can render a gravity meter useless.

SUMMARY AND CONCLUSIONS

A preliminary aquifer injection, storage and recovery program at Lancaster, California, was monitored by the U.S. Geological Survey to evaluate the feasibility of artificially recharging the ground-water system through existing production wells. One component of this study was to measure the response of the water table to injection, which was difficult because the water table averaged 300 feet below land surface. Rather than install many expensive monitoring wells, temporal microgravity surveys were used to monitor the water-table response to injection.

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A gravity-station network, consisting of 20 permanent gravity stations within 1 mile of the injection site, was developed to measure the anticipated shape of the ground-water mounding around the injection wells. Temporal, or time-series, microgravity surveys were conducted at the gravity-station network to measure small changes in gravitational acceleration caused by subsurface changes in mass. In an injection scenario, mass, in the form of water, is added to the aquifer, and the associated change in gravity is measured with a portable gravity meter. A microgravity survey was conducted prior to injection to establish baseline gravity values for the gravity-station network. Subsequent surveys were conducted to monitor the accumulation of mass and determine the areal extent of the anomalous mass with time. Differential leveling was used to assess whether vertical aquifer-system deformation contributed to the measured gravity changes. Only one gravity station required an elevation-change correction, less than 1 microgal, showing that the gravity station elevation changes cannot account for the measured changes in gravity.

Specific yield was estimated to be 0.13 using coupled measurements of gravity and water-level change at an existing monitoring well. The gravity-derived value of specific yield is consistent with the values for this part of the Antelope Valley estimated in previous investigations using lithologic well logs and laboratory tests of similar materials. The calculated specific yield was used to convert the measured changes in gravity for the other locations to water-table changes.

The gravitational effect of an irregular injection mound geometry needs to be considered because the non-slab geometry of the injection mound not directly beneath a gravity station may contribute to the measured vertical component of gravity. To assess the gravitational effect of the injection mound on the gravity measurements used to calculate specific yield, a two-dimensional gravity model was used. The results of the gravity simulations showed that the subjacent mass of the injection mound had a negligible effect on the vertical component of gravity at well 7N/12W-34B1 and, hence, on the specific-yield calculation.

Ground-water-level changes were estimated using the gravity-derived specific yield and measured gravity changes. A simple one-layer, steady-state simulation of ground-water flow was used to predict the shape of an injection mound assuming the gravity-derived specific yield and a range of hydraulic conductivities. The gravity-derived water levels reasonably match the simulated injection mounds along the south-to-north profile for hydraulic conductivities 8 to 18 feet per day. Gravity-derived water levels for the stations farthest east of the injection wells, on the west-to-east profile, were within the range of simulated injection mounds for hydraulic conductivities 15 to 18 feet per day, but the gravity-derived water levels for stations near the injection wells (G2E, GZERO, G1W, and G2W) were lower than simulated water levels. Possible explanation for the discrepancy between the simulated and gravity-derived water levels near the injection site may be the variability of the aquifer properties (hydraulic conductivity and specific yield) and interference from environmental factors associated with the injection site (vibration from the injection wells, electromagnetic fields created from the high-voltage power supply for the injection wells, and buried water-supply pipes) that may affect gravity measurements. Additional data on the aquifer properties and the effect of these environmental factors on gravity measurements are needed to further explain these discrepancies. Ideally, coupled measurements of gravity and water-level change would be made at enough locations to adequately define the variability in specific yield.

The accumulated mass of the injection mound beneath the gravity network was determined using Gauss' theorem. The average injection rate derived from the accumulated mass over the injection period is 3,437 tons per day, or 570 gallon/minute; this is 42 percent of the injection rate into the upper aquifer (about 1,350 gallon/minute). The difference between the injection rate derived from the accumulated mass and the measured injection rate suggests that most of the injection mound was beyond the areal extent of the gravity network. The ground-water flow model results also showed that most of the area over which the water-levels changed was outside the area of the gravity network.

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