Ground-Water and Aquifer-System-Compaction Data From the Lorenzi Site, Las Vegas, Nevada, 1994–99

By Michael T. Pavelko

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
	304.8	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
pound (lb)	0.4536	kilogram
pound per square inch (lb/in^2)	6,895	pascal
millibar (mbar)	100.0	pascal

Temperature: Degrees Fahrenheit (^oF) may be converted to degrees Celsius (^oC) by the following equation: $^oC=5/9\ (^oF-32)$.

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

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ABSTRACT

The U.S. Geological Survey, in cooperation with the Las Vegas Valley Water District (LVVWD) and the Nevada Department of Conservation and Natural Resources, Division of Water Resources, is investigating land subsidence in Las Vegas, Nevada. As part of this study, ground-water levels and aquifer-system compaction are monitored at the Lorenzi site in northwest Las Vegas. The site is near 14 LVVWD wells used to pump ground water during periods of high water demand (May through September) and to provide artificial recharge during the remainder of the year. The data are used to determine relations between water-level fluctuations and aquifer-system compaction, to help calibrate a numerical flow model being developed to simulate aquifer-system compaction at the site, and to help estimate hydraulic properties.

Ground-water-level and aquifer-system-compaction data were collected at the Lorenzi site from November 1994 through December 1999. Water-level data were collected from three nested piezometers in three major aquifers at the site. Ground-water-pumpage and artificial-recharge data are compiled for 14 LVVWD wells near the site. Aquifer-system-compaction data were collected from a borehole extensometer that measures compaction from 12 to 800 feet below land surface.

Data indicate ground-water levels and aquifer-system compaction rates fluctuated cyclically in a manner consistent with alternating seasons of ground-water pumpage and artificial recharge in nearby LVVWD wells. Declining water levels and increased compaction rates correspond to periods of ground-water pumpage. Rising water levels and reduced rates of compaction (or temporary aquifer-system expansion) correspond to periods of artificial recharge. From November 1994 through December 1999, a maximum of 1.0327 inches of aquifer-system compaction occurred at the Lorenzi site. The average annual aquifer-system compaction was about 0.2000 inch.

INTRODUCTION

Decades of ground-water overdraft in Las Vegas Valley, Nevada (fig. 1), have caused aquifer-system compaction and land-surface subsidence. Since the 1930's, local ground-water levels have declined by as much as 300 ft and the land surface has subsided by more than 5 ft in some parts of the valley (Bell and Price, 1993). Land subsidence and associated earth fissuring have caused damage to engineered structures, including buildings, roads, and pipelines (Bell, 1981; Bell and Price, 1993).

Beginning in the 1970's, additional water from the Colorado River was imported into the Las Vegas Valley to meet increased municipal water-supply demands. Ground-water pumpage was reduced and local ground-water levels began to recover. In 1987, LVVWD implemented an artificial-recharge program to store surplus Colorado River water temporarily in the aquifer system and slow the rate of aquifer-system compaction by raising ground-water levels. Despite some water-level recovery, land subsidence in Las Vegas Valley continues. One study has shown that residual compaction from past pumping will continue for years or maybe decades (Waichler and Cochran, 1993).

The U.S. Geological Survey (USGS), in cooperation with the LVVWD and the Nevada Department of Conservation and Natural Resources, Division of Water Resources, has developed a study to investigate land subsidence in Las Vegas Valley. As part of this study, ground-water levels and aquifer-system compaction are measured at the Lorenzi site in northwest Las Vegas (fig. 1). The data are being used to establish relations between water-level fluctuations and aquifer-system compaction, to help calibrate a numerical model that simulates aquifer-system compaction at the site, and to help estimate hydraulic properties. The term compaction, used in this report, refers to both aquifer-system compaction and expansion.

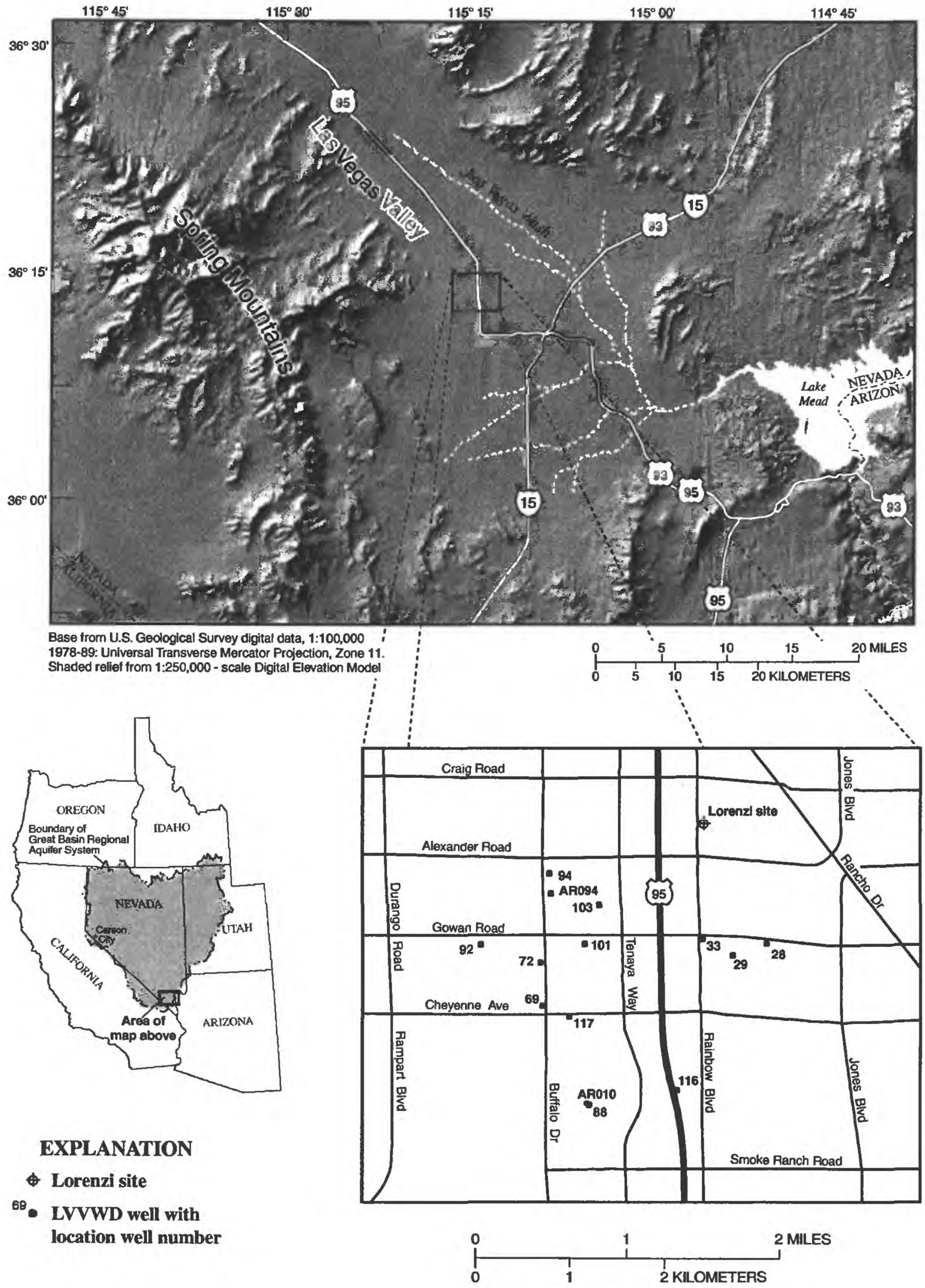

Figure 1. Location of the Lorenzi site and nearby Las Vegas Valley Water District (LVVWD) wells, Las Vegas, Nevada.

Purpose and Scope

This report presents data collected at the Lorenzi site from November 1994 through December 1999 and describes data-collection techniques. This report also presents relations between water-level fluctuations and aquifer-system compaction at the Lorenzi site. This report includes well-construction data for the piezometers and extensometer, geophysical logs from the extensometer borehole, ground-water levels measured in three nested piezometers, and aquifer-system compaction data measured in a borehole extensometer. Ground-water pumpage data for 12 municipal production wells near the Lorenzi site (LVVWD wells 28, 29, 33, 69, 72, 88, 92, 94, 101, 103, 116, and 117; fig. 1) are presented for the period from May through September 1999.

Previous Investigations

Water-resources investigations that deal primarily with land subsidence and related issues in Las Vegas Valley include Malmberg (1964), Mindling (1965; 1971), Bell (1981), Bell and Price (1993), and Pavelko and others (1999). General water-resources investigations that include information about land subsidence in Las Vegas Valley include Maxey and Jameson (1948), Domenico and others (1964), Malmberg (1965), Plume (1989), and Morgan and Dettinger (1996). Domenico and others (1966) examined geologic controls of land subsidence in Las Vegas Valley. Harrill (1976) examined ground-water storage depletion in Las Vegas Valley. Carpenter (1915) examined the general hydrology of Las Vegas Valley. Amelung and others (1999) and Hoffmann (Stanford University, written commun., 1999) examined land subsidence in Las Vegas Valley using interferometric synthetic aperture radar data. Sneed and others (2000) presented preliminary model results for a one-dimensional (vertical), numerical ground-water-flow model of land subsidence for the Lorenzi site.

Location

Las Vegas Valley is in southern Nevada and in the southern part of the Great Basin Regional Aquifer System (fig. 1). The valley is about 1,600 mi^2, with altitudes ranging from about 1,600 ft above sea level on the valley floor to about 12,000 ft above sea level in the Spring Mountains. The northwest-trending valley is bounded on all sides by various mountains. The Las Vegas Wash drains the valley to the east and flows into Lake Mead. Average annual precipitation ranges from about 4 in. on the valley floor to more than 20 in. on the surrounding mountains. Temperatures on the valley floor range from below freezing to over 115^{o}F.

Hydrogeology

The Las Vegas Valley is a structural trough bounded below and on the sides by carbonate, siliciclastic, and igneous bedrock. Alluvial deposits as thick as 5,000 ft overlay the bedrock. The alluvial deposits comprise a stratigraphically complex system of aquifers and aquitards. Major aquifers consist mainly of thick deposits of sand and gravel; major aquitards consist mainly of thick deposits of low permeability silt and clay. The aquifer system also contains numerous thin, laterally discontinuous interbeds of low permeability silt and clay that may be interfingered.

In the central and eastern parts of the valley, the upper 100 to 300 ft of sediment comprise a zone of near-surface aquifers consisting of laterally extensive, complexly interbedded clay, silt, sand, and gravel (Maxey and Jameson, 1948; Morgan and Dettinger, 1996). Caliche and low permeability zones within the near-surface aquifer partially confine underlying developed aquifers (Morgan and Dettinger, 1996). In the western part of the valley, the zone of near-surface aquifers is absent. Shallow layers of caliche and thick clay and silt layers partially confine aquifers in the west. In Las Vegas Valley, most ground water is pumped from aquifers that consist mostly of sand and gravel deposits separated by variably thick clay and silt layers.

Acknowledgments

The author would like to thank the people that provided help in the preparation of this report. Erin Cole of the LVVWD provided information, insights, and data about municipal production wells, ground-water withdrawals, and artificial recharge in Las Vegas Valley. Randell J. Laczniak, USGS, Las Vegas, Nevada; Devin L. Galloway, USGS, Sacramento, California; and Francis S. Riley, USGS, Menlo Park, California provided technical and field assistance. The Nevada Power Company allowed use of land at their Lorenzi substation for operating the monitoring site.

LORENZI SITE

The Lorenzi site is in northwestern Las Vegas, Nevada, at the Nevada Power Company's Lorenzi substation, on Rainbow Boulevard between Craig and Alexander Roads (fig. 1). This site was selected after reviewing previous studies that indicate the surrounding area has a higher rate of land subsidence than other areas of Las Vegas Valley (Harrill, 1976; Bell, 1981). The site is within a 2-mi radius of 14 LVVWD wells used to pump ground water from about May through September and/or to provide artificial recharge from about October through May. Of these 14 wells, LVVWD wells 69, 88, 92, 94, 101, 103, 116, and 117 are used to pump ground water, LVVWD wells AR010 and AR094 are used to artificially recharge the aquifer system, and LVVWD wells 28, 29, 33, and 72 are used to pump and artificially recharge the aquifer system.

The Lorenzi site, established in 1994, consists of three nested piezometers (USGS-PZD, USGS-PZM, and USGS-PZS) and a vertical borehole extensometer (USGS-EXT1; table 1). Geophysical (fig. 2) and lithologic logs from the extensometer borehole indicate the presence of three major aquifers and three major aquitards at the site (Paillet and Crowder, 1996). Geophysical logs indicate the aquifer depths range from 255 to 308, 420 to 500, and 605 to 800 ft below land surface (F.L. Paillet, U.S. Geological Survey, written commun., 1994). The lithologic log indicates that thin layers of caliche are present from land surface to 70 ft below land surface, the major aquifers consist of sand and gravel with interbedded layers of silt and clay, and the major aquitards consist of silt and clay (T.J. Burbey, U.S. Geological Survey, written commun., 1994).

The nested piezometers are protected by a steel-and-wood housing; the extensometer is housed in a wooden shed approximately 20 ft from the piezometers (fig. 3). Additional equipment housed in the shed includes a barometer, air-temperature probes, data logger, data-storage device, electronics-panel box, and all necessary electronic components.

Barometric pressure is measured inside the shed. Air temperature is measured inside the shed, inside the electronics-panel box, and 10 ft below land surface in the extensometer borehole. The electronics-panel box encases a data logger and a data-storage device. A rechargeable battery and a solar panel provide power to the data-collection system. A voltage regulator conditions voltage from the solar panel to the battery. Barometric-pressure, temperature, and battery-voltage data are not presented, but are available upon request from the USGS Las Vegas office.

Piezometers

The three nested piezometers at the Lorenzi site were installed in May 1994. A 16-in. diameter borehole was drilled to a depth of 52 ft below land surface and a 12.25-in. diameter borehole was drilled from 52 to 703 ft below land surface. A 12-in. diameter steel conductor casing extends from land surface to 52 ft below land surface. USGS-PZS and USGS-PZM are constructed of 2-in. diameter polyvinyl chloride (PVC) casing and screen; USGS-PZD is constructed of 2.25-in. outer diameter, acrylonitrile butadiene styrene (ABS) casing and screen. Each piezometer is screened at a depth interval corresponding to an aquifer identified with borehole-geophysical logs. USGS-PZS is screened from 300 to 310 ft below land surface; USGS-PZM is screened from 447 to 457 ft below land surface; and USGS-PZD is screened from 677 to 687 ft below land surface. A gravel pack is in the annular space adjacent to each screened interval. Neat cement in the remaining annular space isolates each screened interval from other zones of the aquifer system. Construction data for each piezometer are listed in table 1 and shown in figure 4.

Extensometer

The borehole extensometer at the Lorenzi site (USGS-EXT1) is a counterbalanced double-pipe extensometer (figs. 4 and 5) that measures vertical aquifer-system compaction. The extensometer borehole was installed in April 1994 by drilling a 16-in. diameter borehole to a depth of 52 ft below land surface and a 10.75-in. diameter hole from 52 to 800 ft below land surface. Vertical-deviation logs collected at the time of drilling indicate that the borehole deviates about 1.75 degrees from vertical. A 12-in. diameter steel conductor casing extends from land surface to 52 ft below land surface and a 6-in. diameter steel "telescoping" casing, extending the length of the hole, is anchored within a cement plug at the bottom of the borehole. A telescoping casing includes slip joints that allow the casing string to lengthen and shorten as vertical deformation occurs. Inclusion of slip joints in an extensometer casing string minimizes frictional stress between the casing and adjacent sediments and

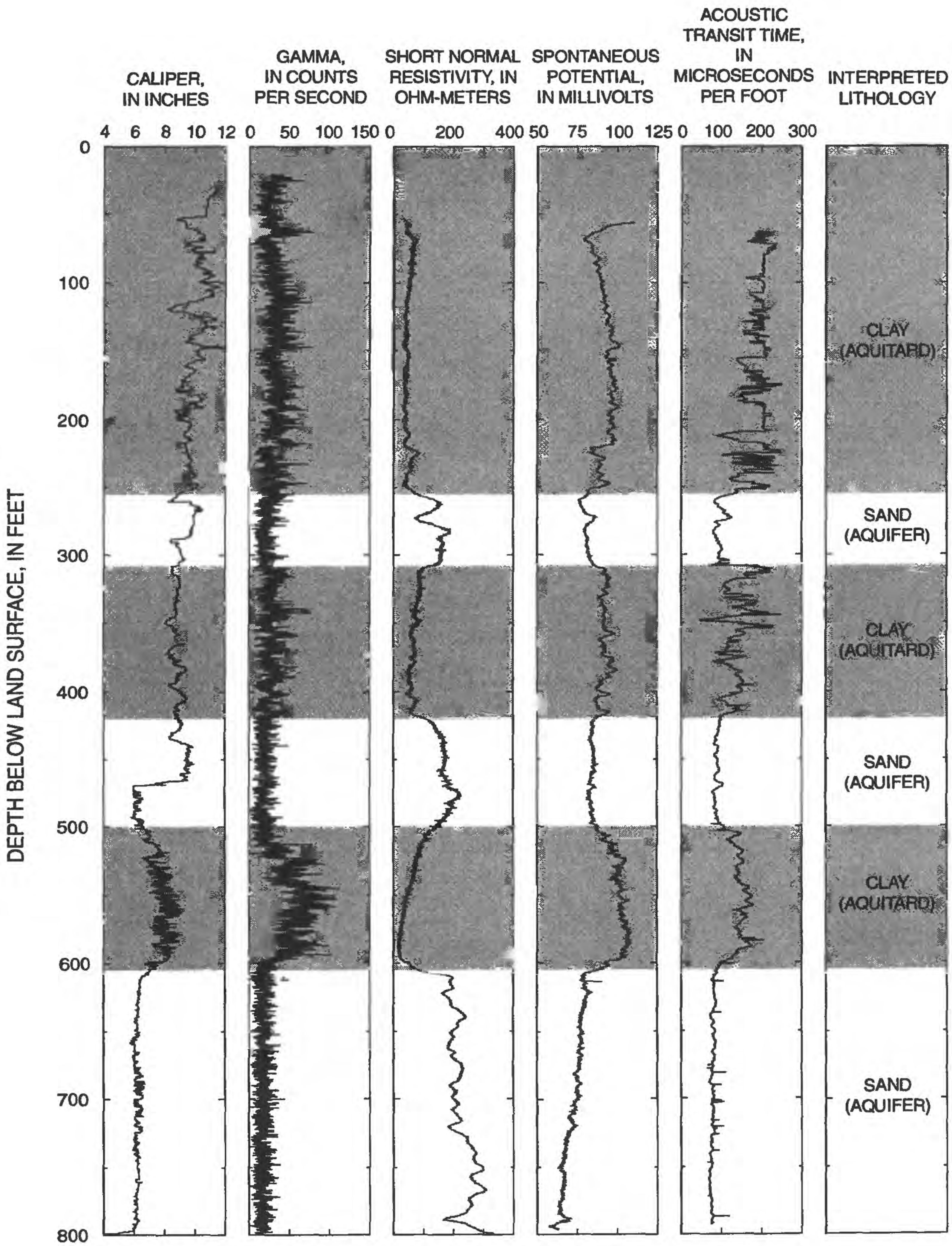

Figure 2. Geophysical logs and interpreted lithology from extensometer USGS-EXT1 at the Lorenzi site, Las Vegas, Nevada.

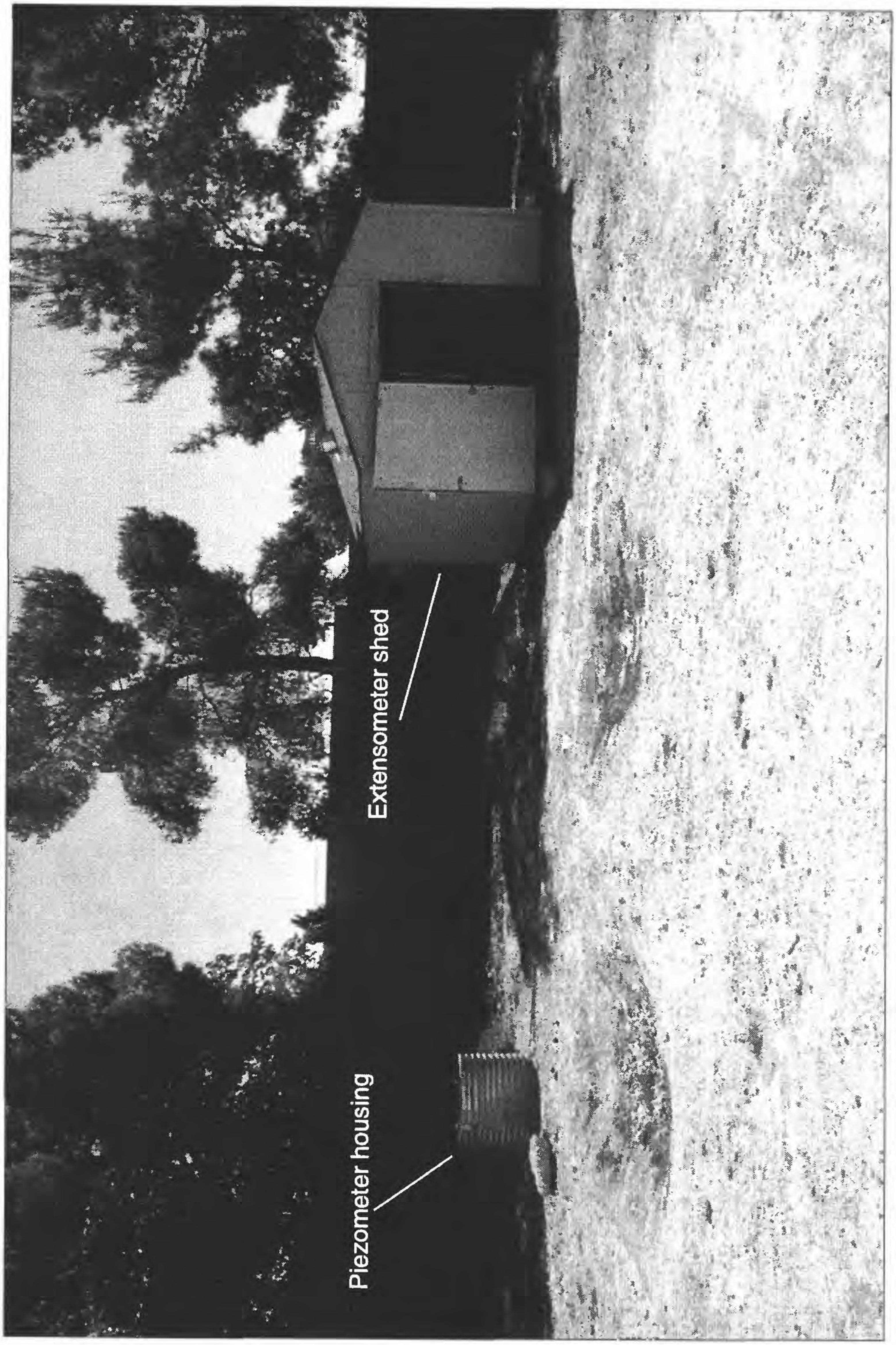

Figure 3. Lorenzi site, Las Vegas, Nevada.

Table 1. Well-construction data for piezometers and the extensometer at the Lorenzi site, Las Vegas, Nevada

[The U.S. Geological Survey (USGS) identifies sites with a unique 15-digit number based on a latitude-longitude grid. The first six digits denote degrees, minutes, and seconds of latitude, the next seven digits denote degrees, minutes, and seconds of longitude, and the last two digits denote a unique sequence number within a 1-second grid of latitude and longitude; --, not applicable]

Well name	USGS site identification number	Date drilled (1994)	Depth	Casing depth	Top of screened interval	Bottom of screened interval
			feet below land-surface			
USGS-PZD	361410115142601	May 18	703	697	677	687
USGS-PZM	361410115142602	May 18	703	467	447	457
USGS-PZS	361410115142603	May 18	703	320	300	310
USGS-EXT1	361410115142604	April 3	800	780	--	--

postpones the onset of casing deformation and failure associated with aquifer-system compaction (Riley, 1986). The 6-in. extensometer casing at the Lorenzi site includes four 10-ft long slip joints. The annular space around the conductor casing is cemented to a depth of 52 ft below land surface. The annular space around the telescoping casing is filled with a heavy bentonite mud. A 2-in. diameter steel extensometer pipe is placed inside the telescoping casing. The extensometer pipe rests atop a cement plug at the bottom of the borehole at a depth of 780 ft below land surface (fig. 4).

A steel extensometer table sits over the extensometer borehole. The table is supported by two steel table legs, which are encased in PVC and anchored 12 ft below land surface. The anchored legs help isolate the table from shallow sediment deformation caused by changes in soil temperature or moisture content. Vertical deformation (compaction or expansion) of the aquifer system is measured by the movement of the table relative to the extensometer pipe. This movement is recorded with a linear potentiometer, an analog chart recorder, and a dial gage (fig. 5). The linear potentiometer is connected to the extensometer table and the top of the extensometer pipe. The analog chart recorder sits atop the extensometer table and is connected to the extensometer pipe by a counterweighted pulley system. The dial gage is attached to the extensometer table and a reference surface attached to the extensometer pipe.

The extensometer pipe is supported above ground by an asymmetric lever system counterbalanced with steel weights. The weight of the extensometer pipe is supported to minimize flexing of the pipe in the borehole. The lever arm is kept level to ensure that the extensometer pipe is aligned with the recording instruments and to further reduce flexing of the extensometer pipe. Riley (1986) indicates flexing of the pipe can result in frictional forces between the pipe and the steel casing, which can degrade the extensometer data. The asymmetric lever system provides a mechanical advantage of 8:1, which reduces the amount of the counterweight needed to support the extensometer pipe.

Riley (1986) describes the complex frictional-stress relations that may occur between an off-vertical casing and a slightly bent extensometer pipe. To quantify the frictional properties of an extensometer, characterize its overall performance, develop confidence in the reliability of its record, and refine the ideal amount of lever counterweight, a dead-band test is performed. The test consists of adding and removing lever counterweights to test the extensometer's ability to return the lever arm to the same position for equal amounts of weight. The dead band of an extensometer is the distance between starting and ending points for equal weights; each amount of weight may have its own dead band. The amount of weight with the smallest dead band is typically the ideal weight for the lever arm (D.L. Galloway, U.S. Geological Survey, oral commun., 2000). Dead-band tests for USGS-EXT1 indicate that 250 lbs of counterweights provide the smallest dead band.

In spite of the above measures, completely eliminating downhole friction in an extensometer is practically impossible and many extensometers experience a degradation of data due to frictional stresses. Step-like shifts in the data are the most noticeable result of downhole friction. These shifts, or "stick-slips," are a result of the extensometer pipe instantaneously releasing frictional pressure that has accumulated over time (Riley, 1986).

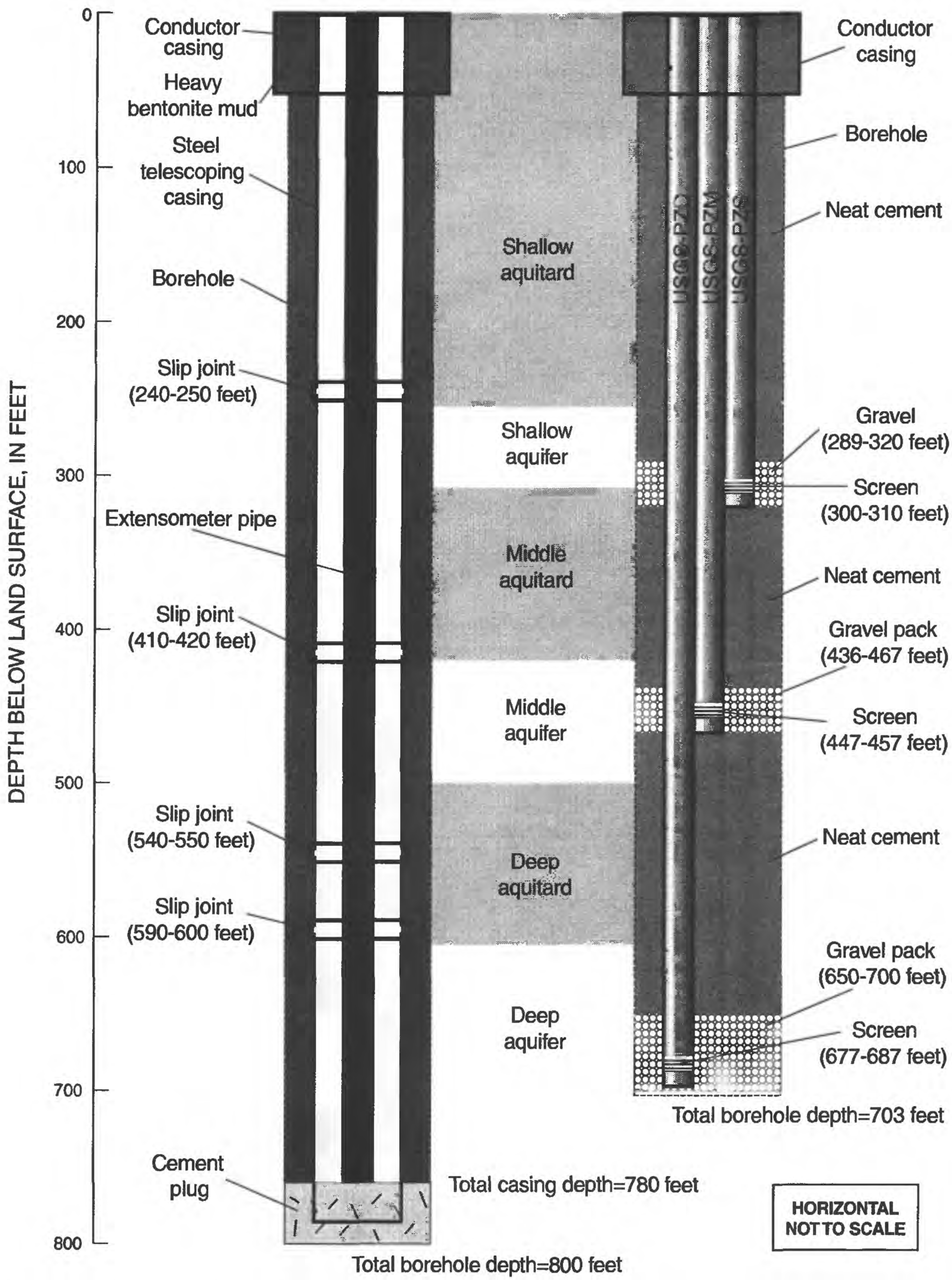

Figure 4. Below-ground construction of the extensometer and piezometers at the Lorenzi site, Las Vegas, Nevada.

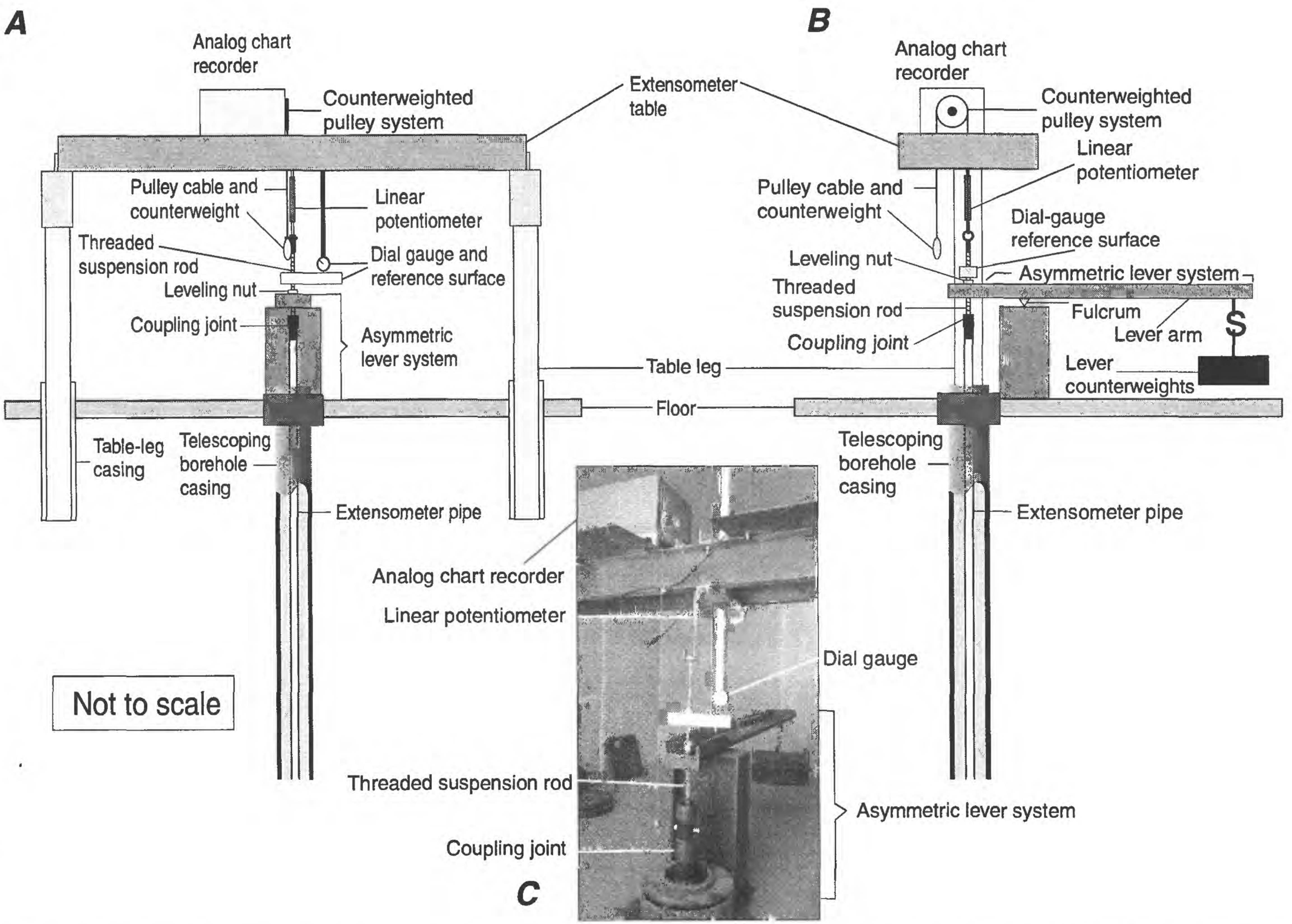

Figure 5. Above-ground construction of the extensometer at the Lorenzi site, Las Vegas, Nevada. *(A)* front view, *(B)* side view (dial gage and near leg not shown), and *(C)* oblique photograph.

GROUND-WATER LEVELS

The depth to water in each piezometer at the Lorenzi site is measured periodically with a graduated steel tape or a calibrated electronic tape (table 2). The graduated steel tape is the preferred device to measure the depth to water because it typically is more accurate than the electronic tape, which is more susceptible to stretching. Steel tape measurements are reported to 0.01 ft and electronic tape measurements are reported to 0.1 ft. The electronic tape is used mainly to measure depth to water when there is excessive condensation in the piezometer casing or when the depth to water is rapidly changing.

The depth to water in each piezometer also is continually monitored with submersible pressure transducers. The transducers in USGS-PZS and USGS-PZM have a pressure range of 0 to 30 lbs/in^2 and the transducer in USGS-PZD has a pressure range of 0 to 50 lbs/in^2. Transducer pressure readings are converted to depth to water and reported to 0.01 ft, which is within the resolution of the transducers. The reported values are not intended to represent the absolute accuracy of the depth-to-water measurements because the transducer measurements are affected by the accuracy of the periodic steel-tape measurements, which are used to calibrate the transducers.

Each transducer is vented at land surface to minimize the potential effects of atmospheric barometric-pressure changes on transducer measurements. Each transducer also measures ground-water temperature. Ground-water-temperature fluctuations can change water density and affect transducer measurements. Barometric pressure is measured at the site with a barometric-pressure sensor that has a range of 800 to 1,100 millibars. Barometric-pressure data are used to determine if barometric-pressure changes affect transducer measurements. Depth to water, water temperature, and barometric pressure are recorded every hour on an electronic data logger.

Continual depth-to-water data for each piezometer, from November 1994 through December 1999, are summarized in table 3 and shown in figure 6*A*. During the period of record, continual depth-to-water measurements ranged from 221.1 to 243.5 ft below land surface in USGS-PZS; 251.9 to 311.5 ft below land surface in USGS-PZM; and 251.5 to 328.8 ft below land surface in USGS-PZD. The variance of depth to water in USGS-PZS (22.4 ft) is considerably less than in USGS-PZM (59.6 ft) and USGS-PZD (77.3 ft). Although USGS-PZS water-level fluctuations are smaller in magnitude, water levels in all three piezometers respond to system stresses in a similar manner (figs. 6*A* and 7*B*).

During the period of record, LVVWD wells near the Lorenzi site generally were pumped during summer months (May through September) and (or) artificially recharged during the remainder of the year (Erin Cole, Las Vegas Valley Water District, written commun., 2000). Water levels in all three piezometers cyclically fluctuated in a manner consistent with the seasonal periods of pumping and artificial recharge. Water levels declined during periods of pumping and rose during periods of artificial recharge. From 1995 to 1997, annual maximum water levels were relatively constant and annual minimum water levels declined in piezometers USGS-PZM and USGS-PZD. From 1997 to 1999, annual maximum and minimum water levels rose in all three piezometers (fig. 6*A*). This general trend is consistent with increased amounts of artificial recharge that began during the winter of 1997-98 (Erin Cole, Las Vegas Valley Water District, written commun., 2000).

Production wells were diurnally pumped during pumping seasons from 1997 to 1999; wells were pumped during the night and the morning and turned off during the day. Prior to 1997, production wells were pumped more continuously during pumping seasons (Erin Cole, Las Vegas Valley Water District, written commun., 2000). Diurnal ground-water pumpage in 1999 and the responses of Lorenzi site ground-water levels are shown in figures 7 and 8. Water levels declined during the pumping season, but fluctuated daily as production wells were cyclically pumped. During periods when daily ground-water pumpage was temporarily decreased, water levels in the piezometers temporarily rose (fig. 7). During seasons of diurnal pumping when pumps were turned off, water levels rose (fig. 8).

Ground-water levels for each piezometer for the period of record are shown in figure 6*A*. Ground-water levels during the 1995 season of near-continuous pumping are shown in figures 9*A* and 10. During seasons of near-continuous pumping, water levels generally decline linearly, except for periods when pumping is reduced. Ground-water levels during the 1999 season of diurnal pumping are shown in figures 7*B* and 8*B*. During seasons of diurnal pumping, a trend of water-level decline is superposed by daily water-level fluctuations. Reductions in daily pumpage result in smaller daily fluctuations (fig. 7). Water levels rise during the

Table 2. Periodic depth-to-water measurements in piezometers at the Lorenzi site, Las Vegas, Nevada, 1995–99

[**Depth to water**: referenced to land-surface; precision of depth to water indicates measurement accuracy; --, water level was not measured or measurement was rejected during data review.
Method: S, steel tape; T, electronic tape; NA, not applicable.
Site status: J, water level measured during artificial recharge of nearby production wells; S, water level measured during pumping of nearby production wells; T, water level measured after pumping of nearby production wells; U, unknown; Z, other]

Date	Water-level measurement						Site status
	USGS-PZD		USGS-PZM		USGS-PZS		
	Depth to water (feet)	Method	Depth to water (feet)	Mathod	Depth to water (feet)	Mathod	
			1995				
04/14/95	276	S	274	S	232	S	Z
05/09/95	277	S	275	S	232	S	T
06/12/95	283	S	275	S	232	S	S
07/28/95	301	S	286	S	238	S	S
08/29/95	309	S	--	NA	240	S	S
10/10/95	306	S	--	NA	241	S	Z
11/03/95	299	S	--	NA	--	NA	Z
			1996				
04/01/96	277	T	274	T	233	T	Z
04/30/96	276	T	273	T	--	NA	Z
07/02/96	298	T	285	T	238	T	S
07/31/96	306	S	291	S	239	S	T
09/16/96	311	T	301	T	243	T	Z
10/09/96	311	T	300	T	--	NA	S
10/22/96	310	T	300	T	243	S	Z
11/05/96	301.90	S	295.77	S	241.50	S	U
11/05/96	--	NA	295.66	S	--	NA	U
11/06/96	--	NA	295.87	S	--	NA	U
11/07/96	301.97	S	295.98	S	241.86	S	U
11/08/96	301.63	S	295.71	S	241.74	S	U
11/13/96	301.63	S	295.20	S	241.22	S	J
11/25/96	297.3	T	292.89	S	240.38	S	J
12/18/96	292.0	T	289.3	T	238.9	T	J
12/19/96	291.3	T	288.9	T	238.6	T	J
12/19/96	291.0	T	288.8	T	238.4	T	J
			1997				
01/14/97	284.9	T	283.86	S	236.26	S	J
02/12/97	283.1	T	280.22	S	234.10	S	U
02/12/97	282.5	T	--	NA	--	NA	U
03/12/97	278.6	T	276.69	S	232.97	S	U
03/15/97	278.1	T	--	NA	--	NA	U
03/19/97	278.9	T	276.55	S	233.27	S	J
04/03/97	277.3	T	274.87	S	232.47	S	J
05/06/97	279.53	T	275.84	S	233.28	S	J
05/07/97	--	NA	275.9	T	--	NA	U
05/08/97	280.3	T	275.98	S	233.22	S	U

Table 2. Periodic depth-to-water measurements in piezometers at the Lorenzi site, Las Vegas, Nevada, 1995-99—Continued

Date	Water-level measurement						Site statue
	USGS-PZD		USGS-PZM		USGS-PZS		
	Depth to water (feet)	Method	Depth to water (feet)	Method	Depth to water (feet)	Method	
1997—Continued							
05/09/97	--	NA	275.6	T	--	NA	U
05/13/97	280.8	T	276.13	S	233.37	S	J
05/19/97	285.9	T	278.7	T	233.9	T	T
06/06/97	301.4	T	286.2	T	235.22	S	S
07/08/97	312.3	T	294.92	S	238.38	S	S
08/07/97	317.7	T	301.34	S	240.35	S	S
09/03/97	312.2	T	306.0	T	241.69	S	T
09/03/97	--	NA	303.6	T	--	NA	T
09/23/97	318.8	T	308.54	S	241.71	S	T
09/24/97	319.9	T	--	NA	--	NA	T
09/24/97	318.8	T	--	NA	--	NA	T
09/25/97	320.6	T	309.4	T	241.7	T	T
10/03/97	314.3	T	307.4	T	241.5	T	S
10/30/97	305.8	T	302.4	T	241.7	T	J
12/01/97	294.0	T	293.0	T	239.2	T	J
12/12/97	291.5	T	290.8	T	238.9	T	J
12/22/97	288.0	T	--	NA	--	NA	J
1998							
01/08/98	282.8	T	283.0	T	235.9	T	J
02/13/98	278.5	T	276.34	S	231.94	S	J
02/26/98	273.8	T	272.48	S	230.33	S	J
03/24/98	271.7	T	269.1	T	228.2	T	J
03/27/98	272.2	T	269.6	T	227.9	T	J
04/23/98	268.6	T	266.6	T	227.0	T	J
05/12/98	270.9	T	267.8	T	227.4	T	J
06/11/98	286.7	T	277.4	T	229.8	T	T
06/25/98	296.7	T	282.3	T	231.3	T	T
06/25/98'	291.4	T	--	NA	--	NA	T
07/13/98	302.1	T	287.1	T	233.8	T	T
08/05/98	300.9	T	290.1	T	236.1	T	T
08/06/98	--	NA	--	NA	236.2	T	T
08/20/98	312.8	T	296.3	T	237.2	T	S
08/21/98	313.6	T	--	NA	--	NA	S
09/14/98	308.4	T	299.0	T	237.5	T	T
09/28/98	319.3	T	304.3	T	238.5	T	S
09/28/98	316.0	T	--	NA	--	NA	T
10/29/98	293.34	S	291.43	S	238.40	S	J
11/25/98	283.59	S	283.56	S	236.20	S	J
12/22/98	276.01	S	276.86	S	233.13	S	J

Table 2. Periodic depth-to-water measurements in piezometers at the Lorenzi site, Las Vegas, Nevada, 1995-99—Continued

Date	Water-level measurement						Site statua
	USGS-PZD		USGS-PZM		USGS-PZS		
	Depth to water (feet)	Method	Depth to water (feet)	Method	Depth to water (feet)	Method	
1999							
01/21/99	268.04	S	269.44	S	229.73	S	J
02/01/99	265.6	T	--	NA	--	NA	J
02/08/99	263.65	S	265.28	S	227.40	S	J
02/10/99	263.3	T	265.0	T	227.3	T	J
02/10/99	263.4	T	265.0	T	227.3	T	J
02/22/99	260.74	S	262.47	S	226.30	S	J
02/28/99	259.79	S	261.32	S	225.73	S	J
03/18/99	257.53	S	258.38	S	224.37	S	J
03/29/99	258.67	S	258.04	S	223.86	S	J
04/11/99	256.79	S	256.22	S	223.08	S	J
04/28/99	252.73	S	252.99	S	222.06	S	J
05/05/99	252.19	S	252.30	S	221.70	S	J
05/28/99	256.69	S	252.49	S	221.53	S	J
06/24/99	279.81	S	265.42	S	224.26	S	S
07/13/99	281.9	T	270.6	T	226.73	S	T
08/10/99	294.43	S	279.17	S	230.55	S	T
09/27/99	309.86	S	292.82	S	234.86	S	T
10/18/99	285.27	S	282.38	S	235.65	S	J
11/17/99	272.18	S	272.10	S	232.65	S	J
12/15/99	266.49	S	266.14	S	229.10	S	J

Table 3. Summary of continual depth-to-water measurements in piezometers at the Lorenzi site, Las Vegas, Nevada, 1994–99

[Depth-to-water measurements are referenced to land surface. Depth-to-water statistics are rounded from the recorded values to the nearest 0.1 ft. Min., minimum hourly value; Mean, average of hourly values; Max., maximum hourly value; value in parentheses is the number of missing hours for indicated period; *, November 1994 consists of only 14 days and 10 hours of measurements; **, 1994 annual values are derived from less than two months of measurements; --, no data]

Month	USGS-PZD				USGS-PZM				USGS-PZS			
	Depth to water				Depth to water				Depth to water			
		Min.	Mean	Max.		Min.	Mean	Max.		Min.	Mean	Max.
1994												
November *		295.7	297.1	298.4		292.4	293.4	294.2		240.1	240.7	241.3
December	(2)	290.0	293.0	296.0		288.2	290.3	292.3		237.8	239.1	240.3
Annual **		290.0	295.0	298.4		288.2	291.8	294.2		237.8	239.9	241.3
1995												
January		284.0	286.8	290.1		283.3	285.6	288.2		235.1	236.4	238.0
February		280.0	281.9	284.1		279.3	281.2	283.3		233.8	234.4	235.2
March	(28)	276.2	278.0	280.0		275.5	277.4	279.3		232.3	233.1	233.8
April		274.8	275.9	278.5		273.2	274.2	275.5		231.5	231.9	232.4
May		277.5	280.4	284.2		274.0	275.6	277.4		231.6	232.2	232.8
June	(95)	281.4	284.6	291.0	(95)	275.4	276.8	279.2	(95)	232.5	233.8	235.1
July		290.2	297.0	301.9		279.3	283.5	287.1		235.0	236.5	238.1
August		301.7	305.4	309.7		287.1	290.4	293.6		237.9	239.0	239.8
September	(25)	308.7	309.7	312.0		293.6	295.7	297.9		239.8	240.4	241.0
October		299.1	304.0	309.0		292.6	295.1	297.0		240.2	240.6	241.0
November		292.5	296.4	299.2		288.7	291.0	292.8		238.4	239.5	240.4
December	(49)	285.8	289.2	292.5	(18)	283.5	286.2	288.7	(33)	236.1	237.5	238.4
Annual	(197)	274.8	290.8	312.0	(113)	273.2	284.4	297.9	(128)	231.5	236.3	241.0
1996												
January		282.2	284.4	285.9		280.3	281.6	283.7		234.2	235.3	236.4
February		281.0	283.5	285.3		278.0	279.3	280.5		233.4	234.0	234.6
March	(21)	277.3	278.5	281.1		274.6	276.0	278.1		232.3	233.0	233.8
April		276.0	276.9	279.4		272.8	273.7	274.8		232.5	232.8	233.3
May		277.0	280.6	285.5		273.1	275.2	276.6		232.7	233.5	234.2
June		283.3	291.3	296.3	(191)	276.3	279.8	283.8		234.2	235.7	237.2
July		295.4	301.7	306.1		283.4	287.8	291.3		236.3	238.2	239.5
August		306.2	313.4	321.3		291.3	297.3	302.8		239.2	240.5	241.8
September	(5)	306.9	313.2	322.8		299.5	302.1	305.1		241.5	242.4	243.3
October	(228)	305.0	308.2	314.3	(228)	298.1	299.7	301.4	(228)	242.6	243.0	243.5
November	(179)	296.1	299.0	302.5	(179)	291.6	293.8	295.8	(179)	239.4	240.6	241.9
December	(9)	287.7	292.7	299.5	(3)	286.2	289.4	292.4	(3)	237.3	238.6	239.8
Annual	(442)	276.0	293.6	322.8	(601)	272.8	286.3	305.1	(410)	232.3	237.3	243.5
1997												
January	(238)	282.0	285.1	287.7		280.8	283.6	286.2		235.0	236.1	237.4
February	(449)	280.8	282.1	283.4		277.9	279.6	283.3		232.9	234.2	235.0
March	(348)	277.6	278.3	279.2	(129)	275.8	276.9	278.7	(2)	232.8	233.2	233.7
April		276.4	278.7	282.2	(720)	--	--	--		232.3	232.8	233.3
May	(167)	279.3	286.9	297.6	(210)	275.3	279.5	284.6	(75)	232.9	233.8	234.9

Table 3. Summary of continual depth-to-water measurements in piezometers at the Lorenzi site, Las Vegas, Nevada, 1994-99—Continued

Month	USGS-PZD				USGS-PZM				USGS-PZS			
		Depth to water				Depth to water				Depth to water		
		Min.	Mean	Max.		Min.	Mean	Max.		Min.	Mean	Max.
1997—Continued												
June		288.1	299.7	308.2		281.4	287.6	292.5		234.8	236.1	237.6
July	(1)	297.6	309.8	318.0	(1)	289.7	295.8	300.5	(1)	237.4	239.0	240.1
August		306.2	314.0	323.0		297.6	301.1	305.9		239.9	240.8	241.8
September	(12)	310.0	320.2	328.7		302.5	307.2	311.2	(665)	241.7	241.8	242.0
October		305.3	311.5	328.8		301.9	305.6	311.5	(63)	241.2	241.8	242.3
November		294.2	299.2	305.3		293.2	297.3	302.0		239.2	240.6	241.8
December	(6)	285.5	290.1	294.8		285.1	289.4	293.2		236.6	238.1	239.6
Annual	(1,221)	276.4	296.3	328.8	(1,060)	275.3	291.2	311.5	(806)	232.3	237.4	242.3
1998												
January		276.7	280.4	285.5		276.6	280.6	285.1		233.4	235.0	236.6
February		273.4	276.0	279.0		272.2	274.8	276.6		230.2	231.7	233.4
March	(6)	269.3	271.4	273.4		268.1	269.9	272.1		227.4	228.8	230.3
April		267.2	269.2	271.8		266.4	267.3	269.2	(1)	226.7	227.1	227.6
May		270.2	274.6	284.0		267.2	269.8	274.6		227.0	227.8	229.1
June	(5)	277.8	289.1	299.2		271.9	278.5	284.2	(5)	229.0	230.3	232.3
July		289.1	298.3	306.6		281.7	286.7	290.8	(224)	232.2	233.5	234.8
August	(1)	296.6	307.4	317.3		288.4	294.1	300.1	(132)	236.0	237.1	238.3
September	(3)	303.5	311.5	320.0		297.1	300.5	304.7		237.4	238.0	238.7
October		292.7	298.9	319.4		290.9	295.5	304.6		238.1	238.7	239.2
November		281.8	286.3	292.7		282.0	286.0	290.9		235.4	236.8	238.1
December	(1)	272.9	277.8	283.3	(1)	274.1	278.3	282.1		231.5	233.8	235.5
Annual	(16)	267.2	286.7	320.0	(1)	266.4	281.8	304.7	(362)	226.7	233.2	239.2
1999												
January		265.4	269.5	274.9		267.0	270.8	274.3		228.4	230.3	231.8
February	(2)	259.5	262.4	265.6		261.1	264.0	267.2		225.6	226.9	228.7
March		256.6	259.1	261.6		257.4	259.3	261.2	(1)	223.4	224.4	225.5
April		252.5	256.2	258.0		252.9	255.7	257.5	(1)	222.1	223.0	223.4
May		251.5	254.0	256.9		251.9	252.5	253.3		221.1	221.6	222.1
June		256.7	272.0	284.2		252.3	260.8	268.1		221.5	222.9	225.5
July	(1)	275.6	283.8	291.8	(1)	266.2	271.2	276.2	(1)	225.4	227.3	229.4
August		282.9	293.3	303.0		274.3	279.8	285.9		229.3	231.1	232.6
September		294.5	303.2	310.7		284.1	289.0	293.7		232.5	234.0	235.4
October		278.2	285.8	296.9		277.2	282.8	289.6		234.8	235.4	236.0
November		268.5	273.5	278.2		268.7	273.0	277.2		230.9	233.1	234.8
December		262.1	265.8	269.2		262.4	265.6	268.7		226.4	228.9	230.9
Annual	(3)	251.5	273.2	310.7	(1)	251.9	268.7	293.7	(3)	221.1	228.2	236.0
Period of record	(1,881)	251.5	288.6	328.8	(1,776)	251.9	283.0	311.5	(1,709)	221.1	234.8	243.5

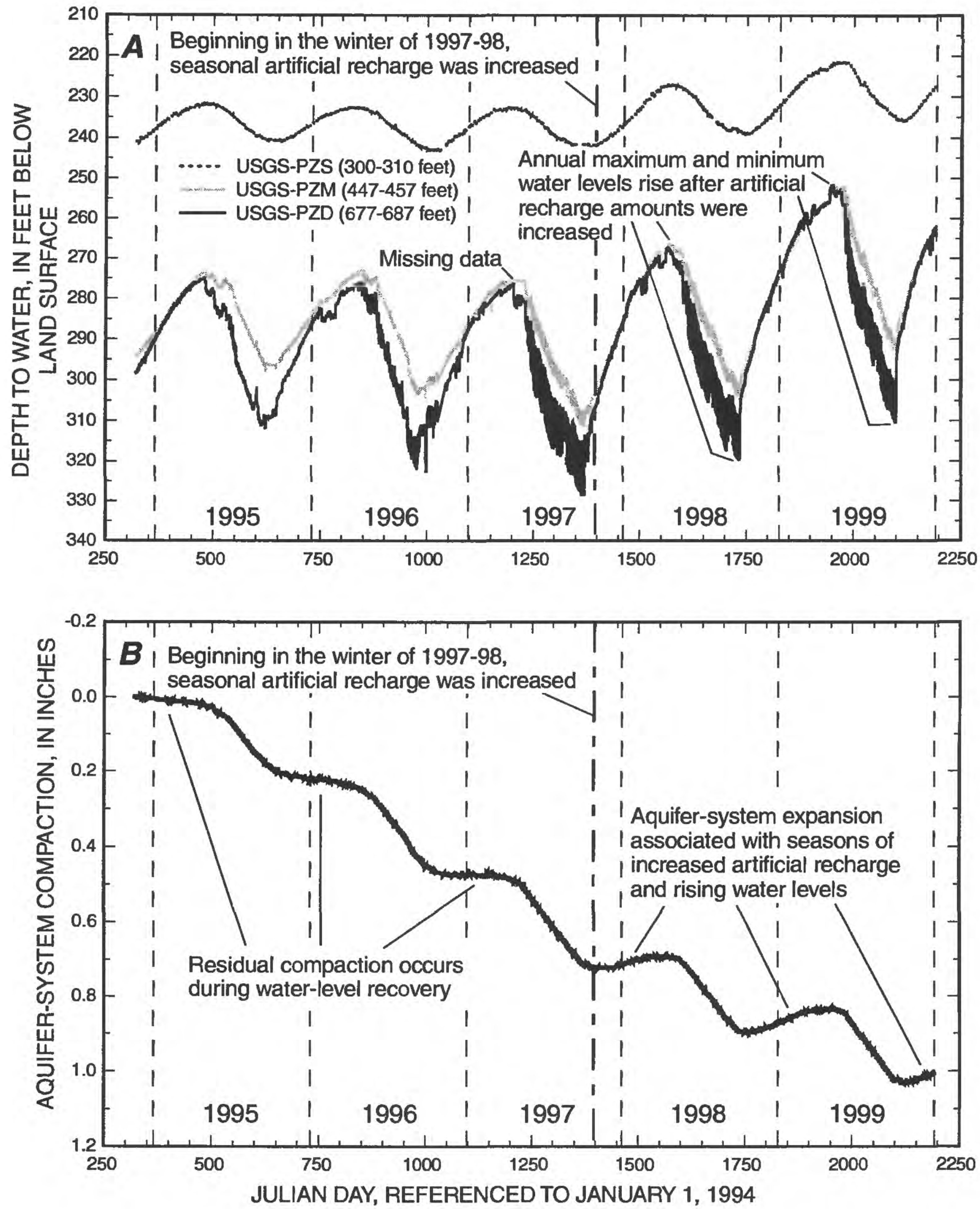

Figure 6. *(A)* Ground-water levels in piezometers USGS-PZS, -PZM, and -PZD and *(B)* aquifer-system compaction in extensometer USGS-EXT1, at the Lorenzi site, Las Vegas, Nevada, November 16, 1994–December 31, 1999.

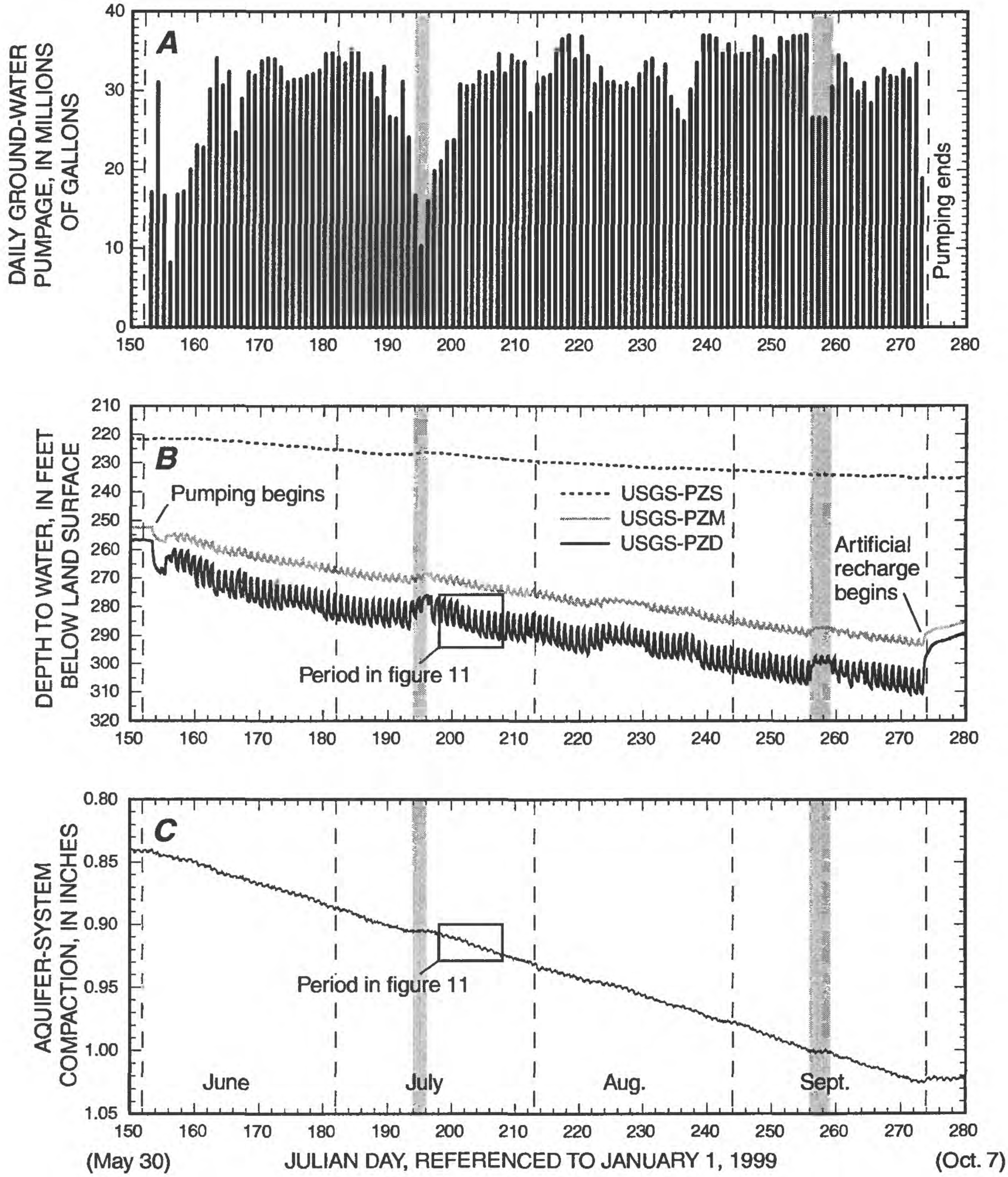

Figure 7. *(A)* Daily ground-water pumpage from production wells near the Lorenzi site, *(B)* ground-water levels in piezometers USGS-PZS, -PZM, and -PZD, and *(C)* aquifer-system compaction in extensometer USGS-EXT1, during a season of diurnal pumping, at the Lorenzi site, Las Vegas, Nevada, May 30–October 7, 1999. [Ground-water pumpage in *(A)* is from LVVWD wells 28, 29, 33, 69, 72, 88, 92, 94, 101, 103, 116, 117. Shaded areas are periods when daily water levels remain high during periods of reduced ground-water pumpage.]

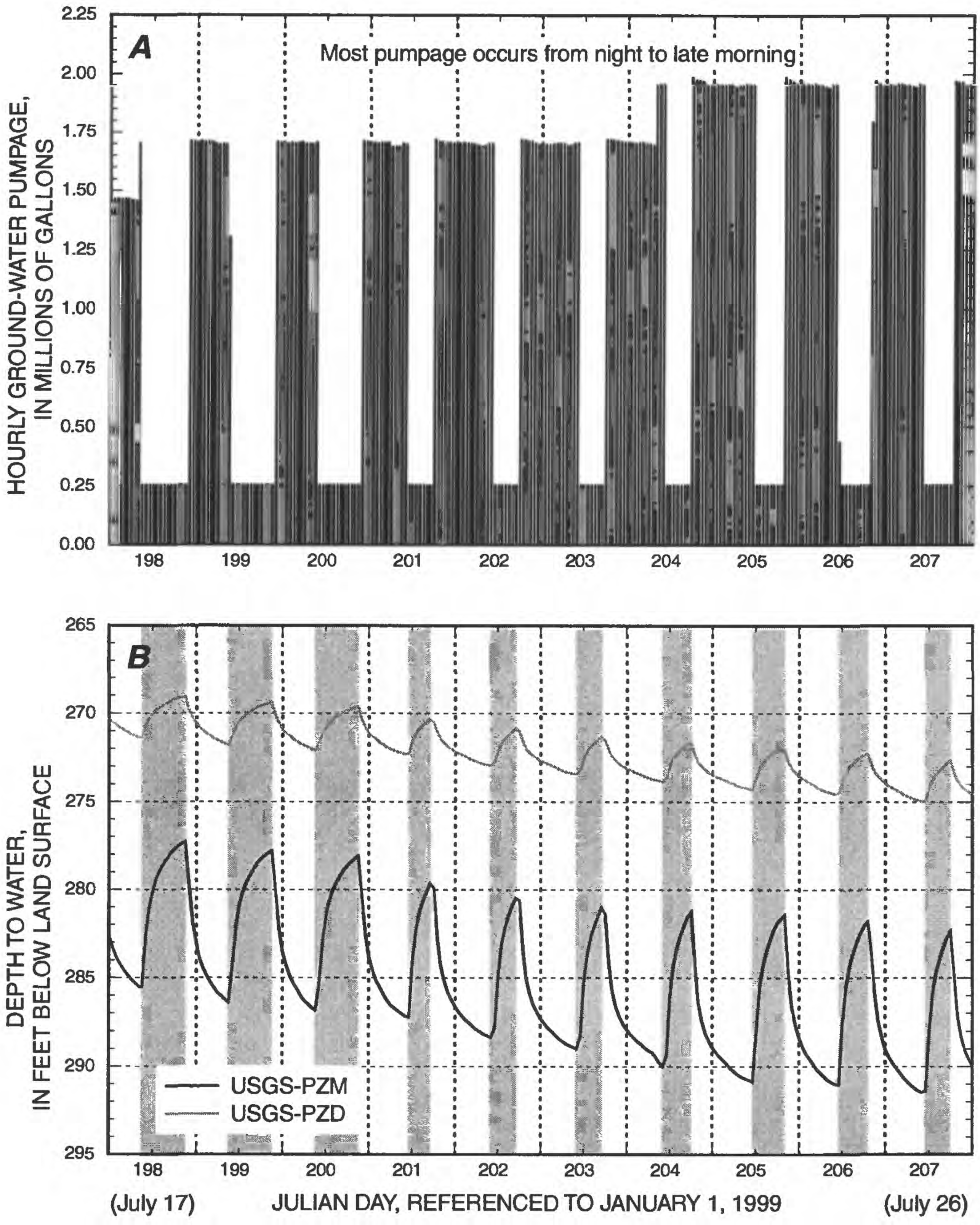

Figure 8. *(A)* Hourly ground-water pumpage from production wells near the Lorenzi site and *(B)* ground-water levels in piezometers USGS-PZM and -PZD, during a period of diurnal pumping, at the Lorenzi site, Las Vegas, Nevada, July 17–26, 1999. [Ground-water pumpage in *(A)* is from LVVWD wells 28, 29, 33, 69, 72, 88, 92, 94, 101, 103, 116, and 117, and shaded areas in *(B)* are periods of decreased pumpage.]

day when pumps are turned off (fig. 8*B*); daily water-level fluctuations in USGS-PZD were about 8 ft during diurnal pumping seasons (fig. 11). Ground-water levels during the 1998–99 season of artificial recharge are shown in figures 12*A* and 13. During seasons of artificial recharge, water levels generally rise with a linear trend, except for periods when artificial recharge is reduced and water levels temporarily decline (fig. 12*A*). Water levels in USGS-PZD are usually the deepest of the three piezometers at the Lorenzi site, but become shallower than those in USGS-PZM after extended periods of artificial recharge (figs. 12*A* and 13) and become deeper when artificial recharge is reduced (fig. 12*A*).

AQUIFER-SYSTEM COMPACTION

Aquifer-system compaction monitored by the borehole extensometer at the Lorenzi site is measured with a linear potentiometer, an analog chart recorder, and a dial gage. The linear potentiometer is the primary measuring device at the site. A linear potentiometer measures changes in distance and outputs the distance changes (compaction) as changes in millivolts. The potentiometer range of motion is 3.937 in. and compaction is reported to 1.0 in. x 10^{-4} in., which is within the resolution of the potentiometer. Potentiometer output is recorded every hour on an electronic data logger and retrieved periodically. Potentiometer output is converted from millivolts to compaction by applying a linear relation derived from calibration data. The reported potentiometer readings are not intended to represent the absolute accuracy of the aquifer-system compaction measurements because the potentiometer measurements are affected by the accuracy of the dial-gage measurements, which are used to calibrate the potentiometer. The analog chart recorder provides a continuous record of compaction data and ensures data are collected if the linear potentiometer or electronic data logger malfunctions. Readings from the dial gage are recorded manually during site visits and are used to evaluate potentiometer performance.

Aquifer-system compaction measured with the linear potentiometer during the period of record is shown in figure 6*B*. Compaction data are cumulatively measured relative to the first day of record (November 16, 1994) and do not represent the total amount of compaction that has occurred at the Lorenzi site. Aquifer-system compaction is measured between a depth of 12 ft below land surface (bottom of the extensometer table legs) and 800 ft below land surface (bottom of the extensometer borehole). The borehole extensometer at the Lorenzi site cannot measure total land subsidence because compressible sediments are below the depth of the extensometer borehole.

During the period of record, a maximum of 1.0327 in. of aquifer-system compaction was measured at the Lorenzi site (fig. 6*B*). The average annual net compaction, which equals total compaction minus total expansion, was about 0.2000 in. From 1994 to 1997, aquifer-system expansion was minimal and the average annual net compaction was about 0.2370 in. From 1998 to 1999, the period coinciding with increased artificial recharge and higher annual water levels, the average annual rate of compaction, including compaction and expansion, was about 0.1445 in. During the period of record, the average rate of compaction for a pumping season was about 0.2224 in. During the 1997–98 artificial-recharge season, about 0.0342 in. of aquifer-system expansion occurred and during the 1998–99 artificial-recharge season, about 0.0669 in. of aquifer-system expansion occurred. Aquifer-system compaction fluctuated seasonally in a manner similar to water-level fluctuations in the piezometers (fig. 6). The greatest rates of aquifer-system compaction correspond to periods of declining water levels in the piezometers and reduced rates of compaction, or aquifer-system expansion correspond to periods of rising water levels in the piezometers. During the 1994–95, 1995–96, and 1996–97 seasons of artificial recharge, residual compaction, which occurs when water-levels are not declining (Ireland and others, 1984), was measured (figs. 6 and 9).

Aquifer-system compaction during the 1995 season of near-continuous pumping is shown in figures 9*B* and 10 and aquifer-system compaction for the 1999 season of diurnal pumping is shown in figures 7*C* and 11. During seasons of near-continuous and diurnal pumping, aquifer-system compaction occurred at a relatively constant rate. When water levels temporarily rose by more than about 9 ft during periods of reduced pumping, aquifer-system compaction rates decreased (fig. 7). Aquifer-system compaction during the 1998–99 season of artificial recharge is shown in figures 12*B* and 13. During the 1995–96 and 1996–97 seasons of artificial recharge, aquifer-system compaction rates were less than during the intervening seasons of near-continuous pumping (fig. 6*B*). During the 1997–98 and 1998–99 seasons of artificial recharge, aquifer-system

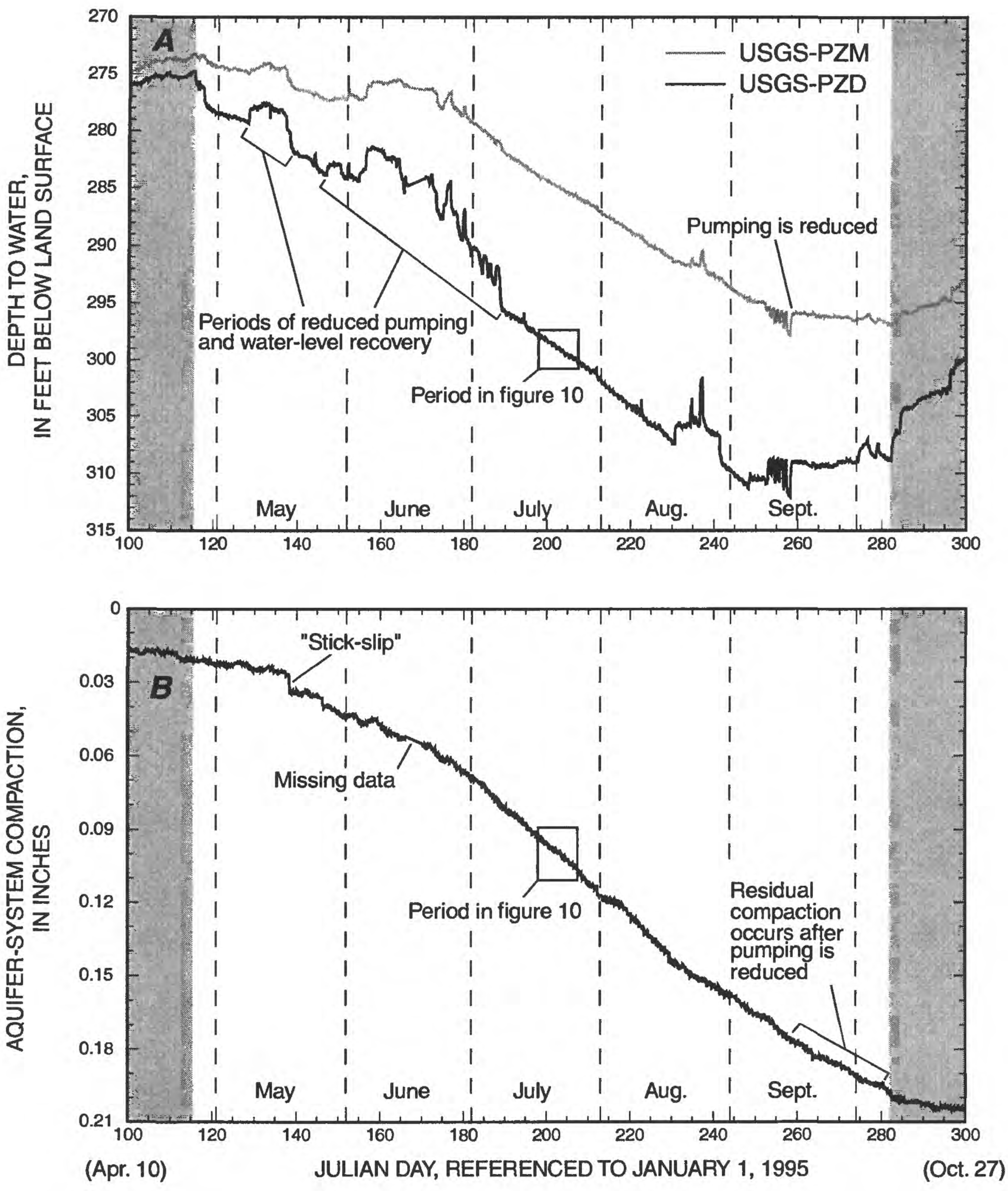

Figure 9. *(A)* Ground-water levels in piezometers USGS-PZM and -PZD and *(B)* aquifer-system compaction in extensometer USGS-EXT1, during a season of near-continuous pumping of nearby production wells, at the Lorenzi site, Las Vegas, Nevada, April 10–October 27, 1995. [Shaded areas are periods when the majority of LVVWD wells are not pumping.]

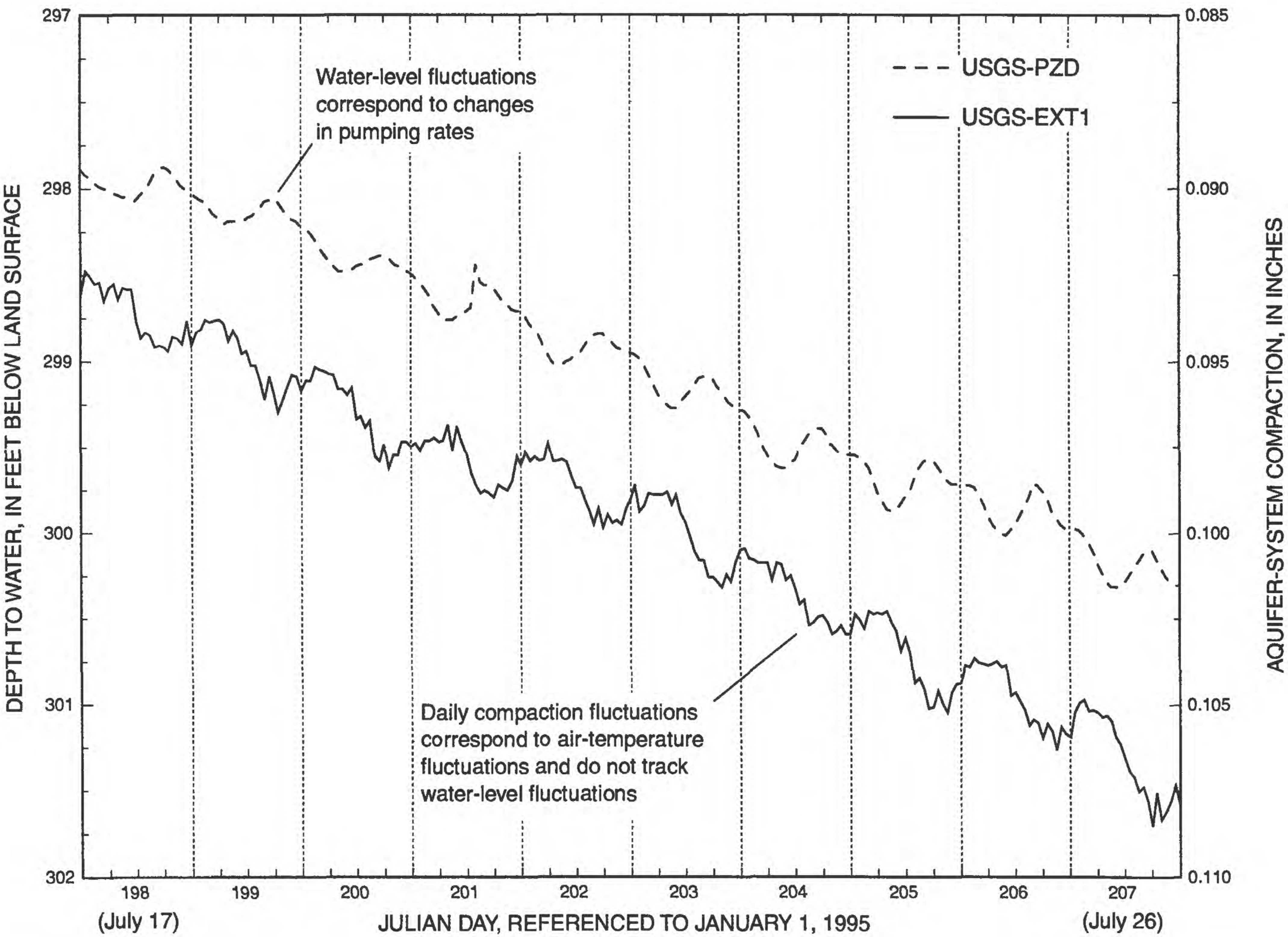

Figure 10. Ground-water levels in piezometer USGS-PZD and aquifer-system compaction in extensometer USGS-EXT1, during a period of near-continuous pumping of nearby production wells, at the Lorenzi site, Las Vegas, Nevada, July 17–26, 1995.

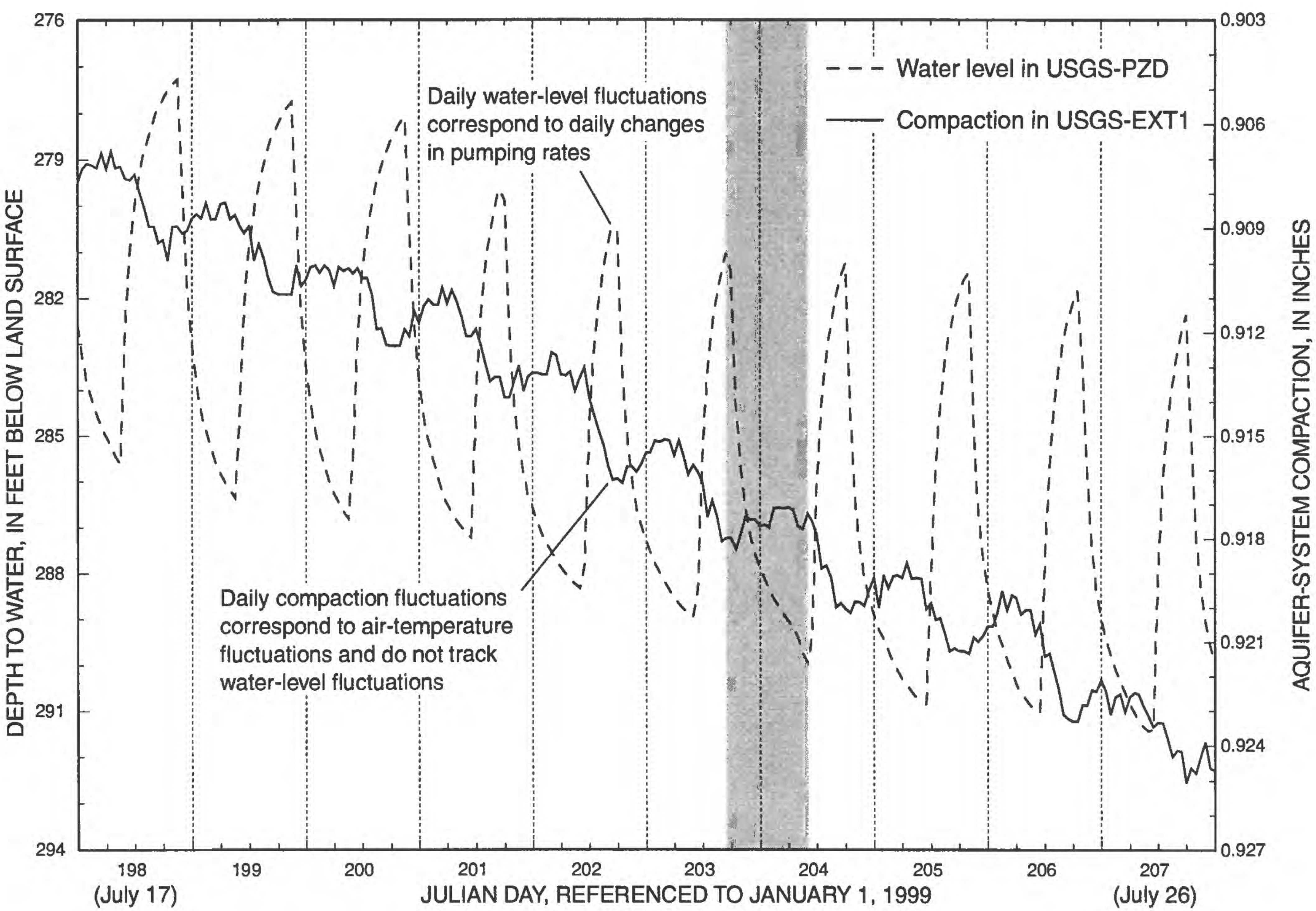

Figure 11. Ground-water levels in piezometer USGS-PZD and aquifer-system compaction in extensometer USGS-EXT1, during a period of diurnal pumping of nearby production wells, at the Lorenzi site, Las Vegas, Nevada, July 17–26, 1999. [Shaded area is an example of a period of water-level decline not associated with aquifer-system compaction.]

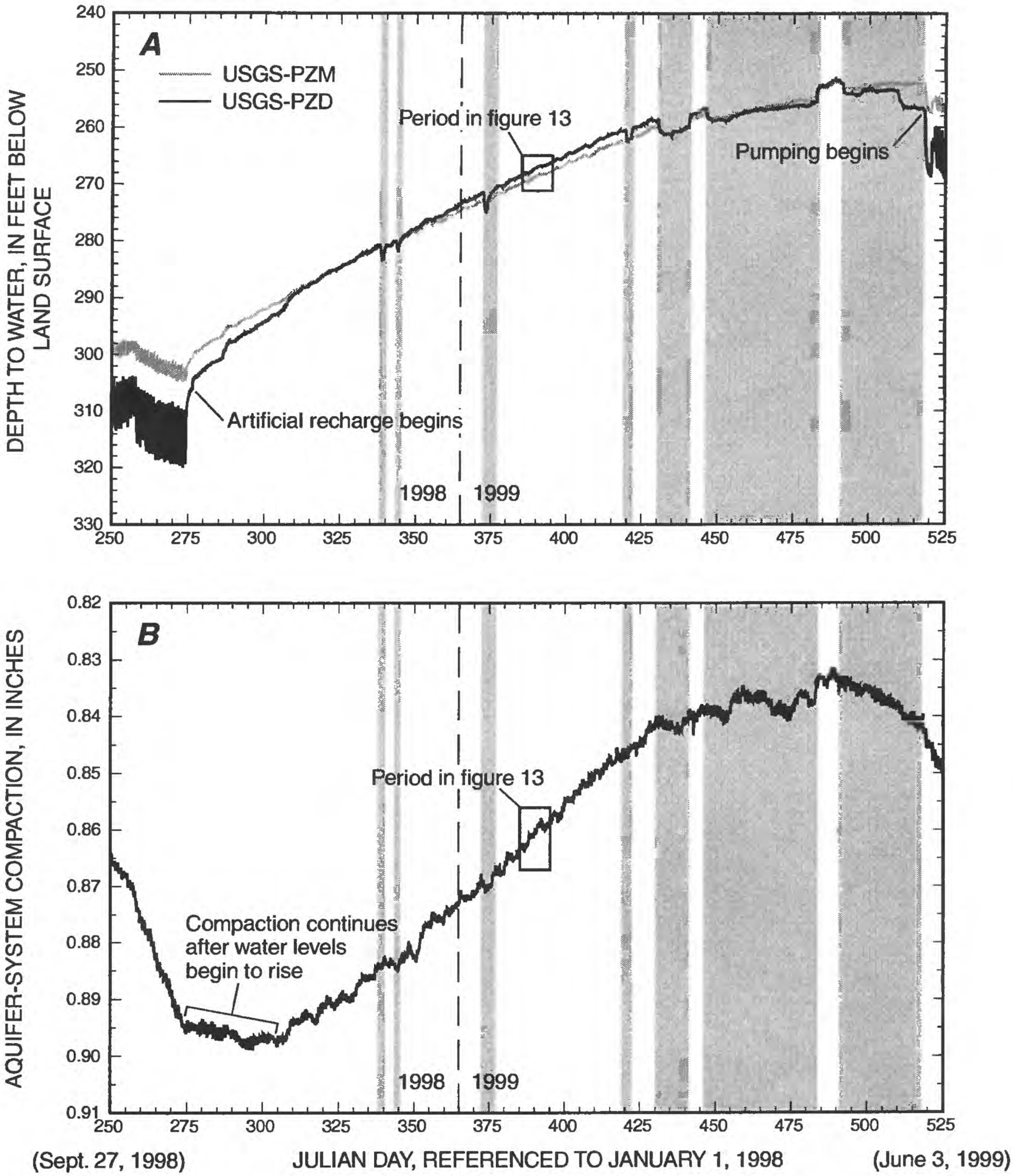

Figure 12. *(A)* Ground-water levels in piezometers USGS-PZM and -PZD, and *(B)* aquifer-system compaction in extensometer USGS-EXT1, during a season of artificial recharge of nearby recharge wells, at the Lorenzi site, Las Vegas, Nevada, September 27, 1998–June 3, 1999. [Shaded areas are periods of reduced artificial recharge.]

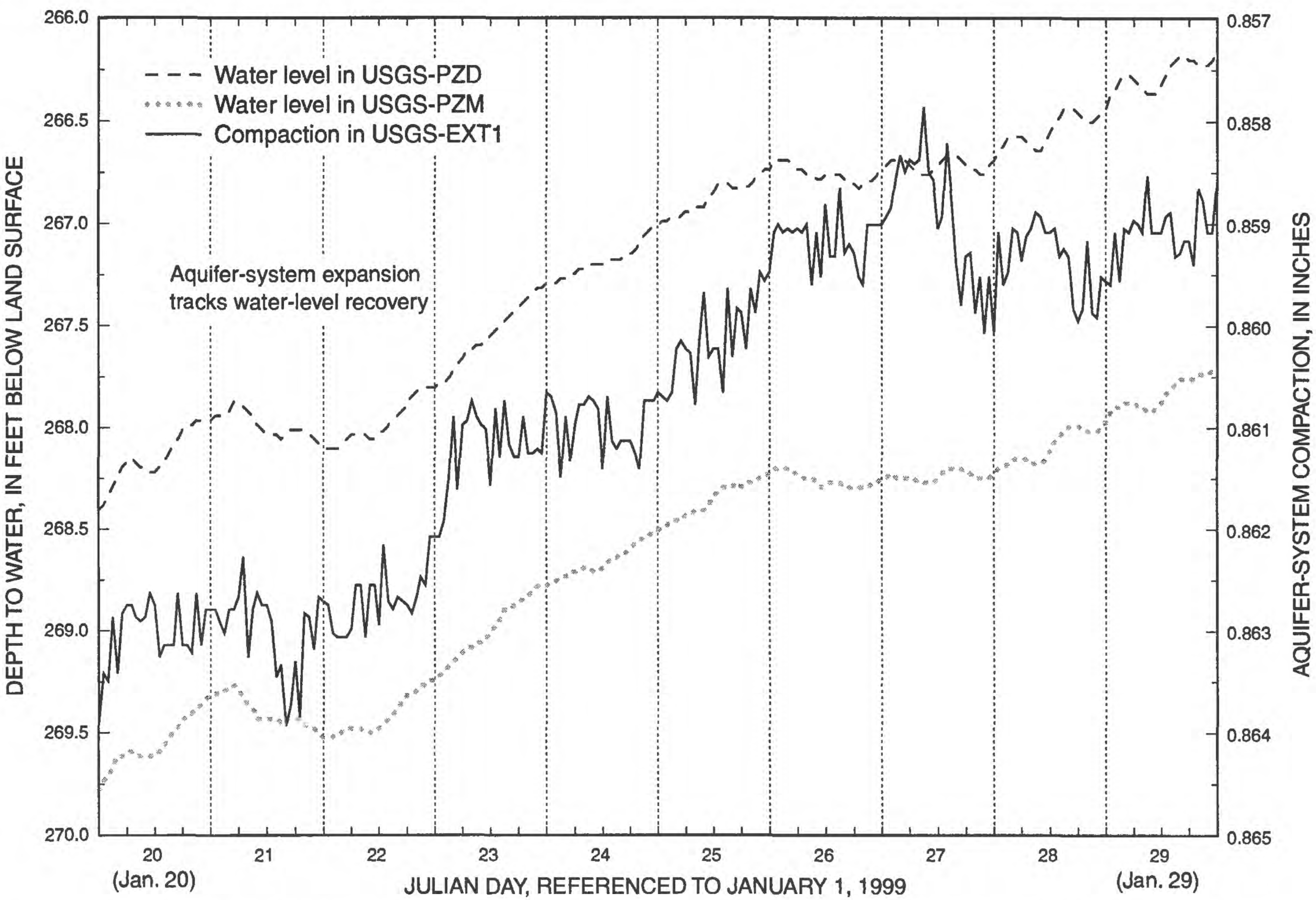

Figure 13. Ground-water levels in piezometers USGS-PZM and -PZD, and aquifer-system compaction in extensometer USGS-EXT1, during a period of artificial recharge of nearby recharge wells, at the Lorenzi site, Las Vegas, Nevada, January 20–29, 1999.

expansion occurred at a relatively constant rate, except for periods when artificial recharge was decreased and aquifer-system compaction occurred (figs. *6B* and *12B*).

Figure *9B* shows the effect of downhole frictional stresses on the extensometer record. The effect, sometimes referred to as "stick-slip," is revealed as a step-like shift in the compaction record and is caused by the instantaneous release of frictional stress that builds up at a point (or points) of contact between the extensometer pipe and the borehole casing (Riley, 1986). Stick-slip is often associated with changes in aquifer-system stress associated with quickly declining water levels (F.S. Riley, U.S. Geological Survey, oral commun., 2000). In figure 9, about 3.5 ft of water-level decline precedes the stick-slip.

Daily aquifer-system compaction fluctuations during seasons of pumping are contrary to seasonal trends: daily compaction corresponds to rising ground-water levels and daily expansion corresponds to declining ground-water levels (figs. 10 and 11). The magnitude of daily compaction fluctuations during periods of near-continuous pumping, when water-level fluctuations are relatively small, are about the same as daily compaction fluctuations during periods of diurnal pumping, when water-level fluctuations are relatively large (figs. 10 and 11). No daily compaction fluctuations are during cooler months, when daily temperatures do not fluctuate as much (fig. 13). Analyses of the extensometer shed-temperature data reveal that the periods of daily compaction associated with rising in ground-water levels correspond to periods of increasing shed temperature, which often exceed 120°F during summer days. Temperature fluctuations cause the metal components of an extensometer to expand and contract, and can cause the extensometer table to move relative to the extensometer pipe. The temperature induced motion can be detected by the linear potentiometer and recorded as compaction or expansion (D.L. Galloway, U.S. Geological Survey, oral commun., 1999). Barometric-pressure changes can cause air to move in to or out of the extensometer borehole. The moving air can affect the borehole air temperature and potentially cause the extensometer pipe to expand or contract, adversely affecting the extensometer record (Evans and Pool, 2000). However, analyses of barometric-pressure, borehole-air temperature, and extensometer data at the Lorenzi site indicate that barometric-pressure and borehole-air temperature fluctuations do not affect the extensometer data.

SUMMARY

During the period of record, water levels in piezometers at the Lorenzi site cyclically fluctuated in a manner consistent with alternating seasons of ground-water pumpage and artificial recharge in nearby production wells: declining water levels corresponded to periods of ground-water pumpage and rising water levels corresponded to periods of artificial recharge. Continual depth-to-water measurements ranged from 221.1 to 243.5 ft below land surface in USGS-PZS, from 251.9 to 311.5 ft below land surface in USGS-PZM, and from 251.5 to 328.8 ft below land surface in USGS-PZD.

During the period of record, aquifer-system compaction rates at the Lorenzi site cyclically fluctuated in a manner similar to water levels in the piezometers. Periods of greatest compaction rates corresponded to declining water levels and periods of reduced compaction rates or aquifer-system expansion corresponded to periods of rising water levels. During the period of record, a maximum of 1.0327 in. of aquifer-system compaction was measured at the Lorenzi site. The average annual rate of compaction, including compaction and expansion, was about 0.2000 in. From 1994 to 1997, the average annual rate of compaction, including compaction and expansion, was about 0.2370 in. and from 1998 to 1999, the average annual rate of compaction, including compaction and expansion, was about 0.1445 in. During the period of record, the average rate of compaction for a pumping season was about 0.2224 in. During the 1997–98 artificial-recharge season, about 0.0342 in. of aquifer-system expansion occurred and during the 1998–99 artificial-recharge season, about 0.0669 in. of aquifer-system expansion occurred.

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