U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the COACHELLA VALLEY WATER DISTRICT

WATER-RESOURCES INVESTIGATIONS REPORT 97-4237

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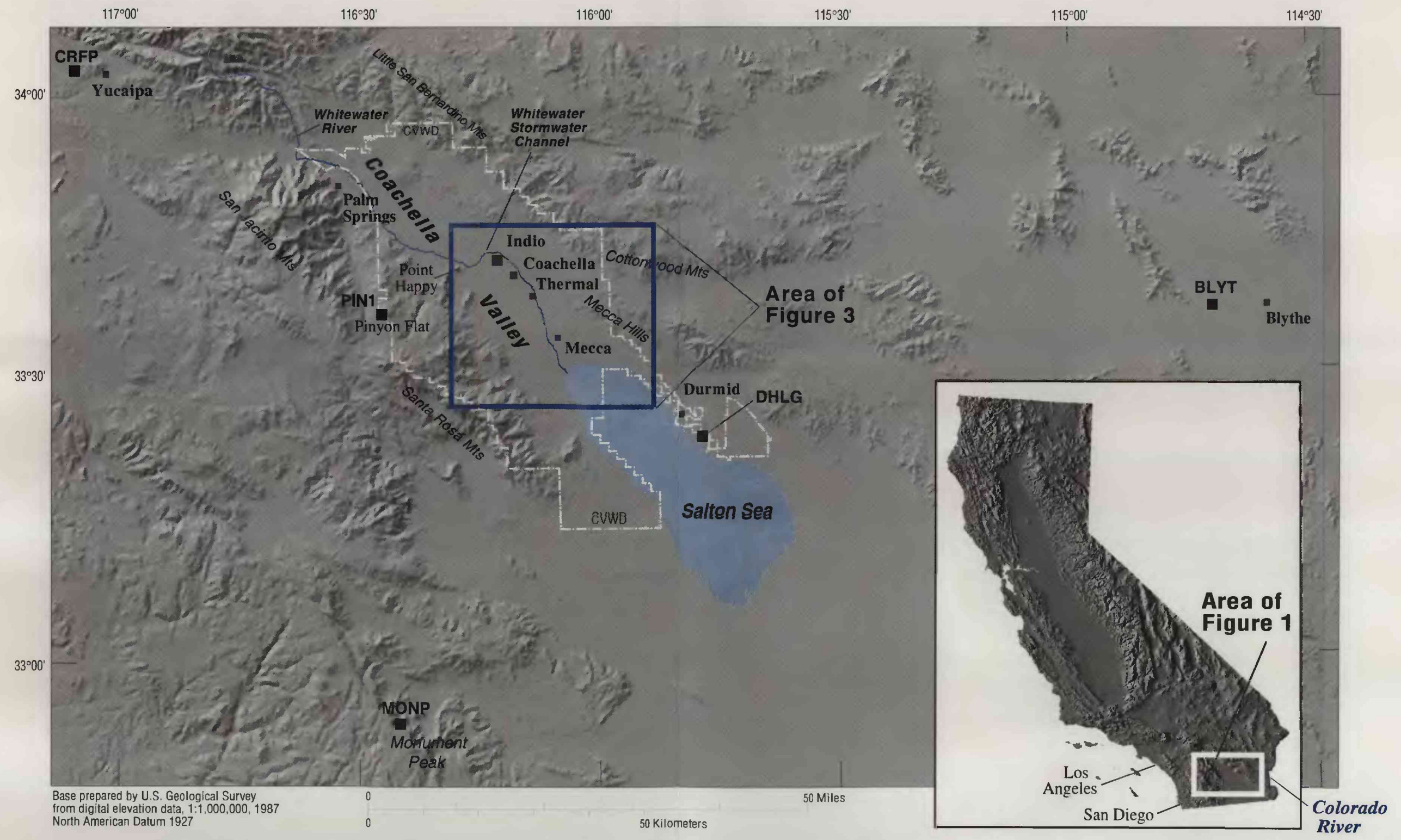
Geodetic Network to Evaluate Historical Elevation Changes and to
Monitor Land Subsidence in Lower Coachella Valley, California, 1996

INTRODUCTION

In the lower Coachella Valley, in the Colorado Desert Region of southern California, ground water has been an important source for agricultural, municipal, and domestic water supplies since the early 1920's. Pumping of ground water resulted in water-level declines of as much as 50 ft between the early 1920's and the late 1940's before the importation of Colorado River water in 1949. As a result of the availability of a surface-water supply, pumping of ground water was reduced, and water levels recovered throughout most of the valley from the 1950's through the 1970's. Since the late 1970's, however, the demand for water has exceeded the deliveries of imported surface water, and ground-water levels have been declining again as a result of increased pumping. Ground-water levels in many areas currently (1996) are lower than previously recorded low levels. These observed water-level declines have the potential to induce new or renewed lowering of land-surface elevations (land subsidence) in the lower Coachella Valley. Land subsidence can result in the disruption of surface drainage, reduction of aquifer-system storage, the formation of earth fissures, and damage to wells, buildings, roads, and utility infrastructure.



Base prepared by U.S. Geological Survey from digital elevation data, 1:1,000,000, 1987
North American Datum 1927

Figure 1—Lower Coachella Valley and surrounding areas including locations of five Continuously Operating Reference Stations (CORS), indicated by solid black squares.

In 1996, the Coachella Valley Water District (CVWD) entered into a cooperative agreement with the U.S. Geological Survey (USGS) to establish a geodetic network of monuments because of concerns related to the potential for land subsidence in the lower Coachella Valley. The purpose of this report is to document the findings of the study done to determine the possible existence, location, and magnitude of land subsidence and to obtain baseline measurements for the accurate determination of future land subsidence in lower Coachella Valley. Initially, historical leveling data for existing geodetic monuments in the lower Coachella Valley were reviewed to determine the geographic extent of the monuments and the frequency and accuracy of the measurements. Existing and new geodetic monuments were selected and field-checked for inclusion in the land-subsidence monitoring network. The network was designed to conform with the guidelines for the spacing of monuments in Global Positioning System (GPS) networks to achieve a vertical accuracy of +/- 0.07 ft (2 cm) (Zilkoski and Frakes, 1996). Land-surface elevation changes at the geodetic monuments were computed by comparing current elevations measured by GPS surveying with historical leveling measurements.

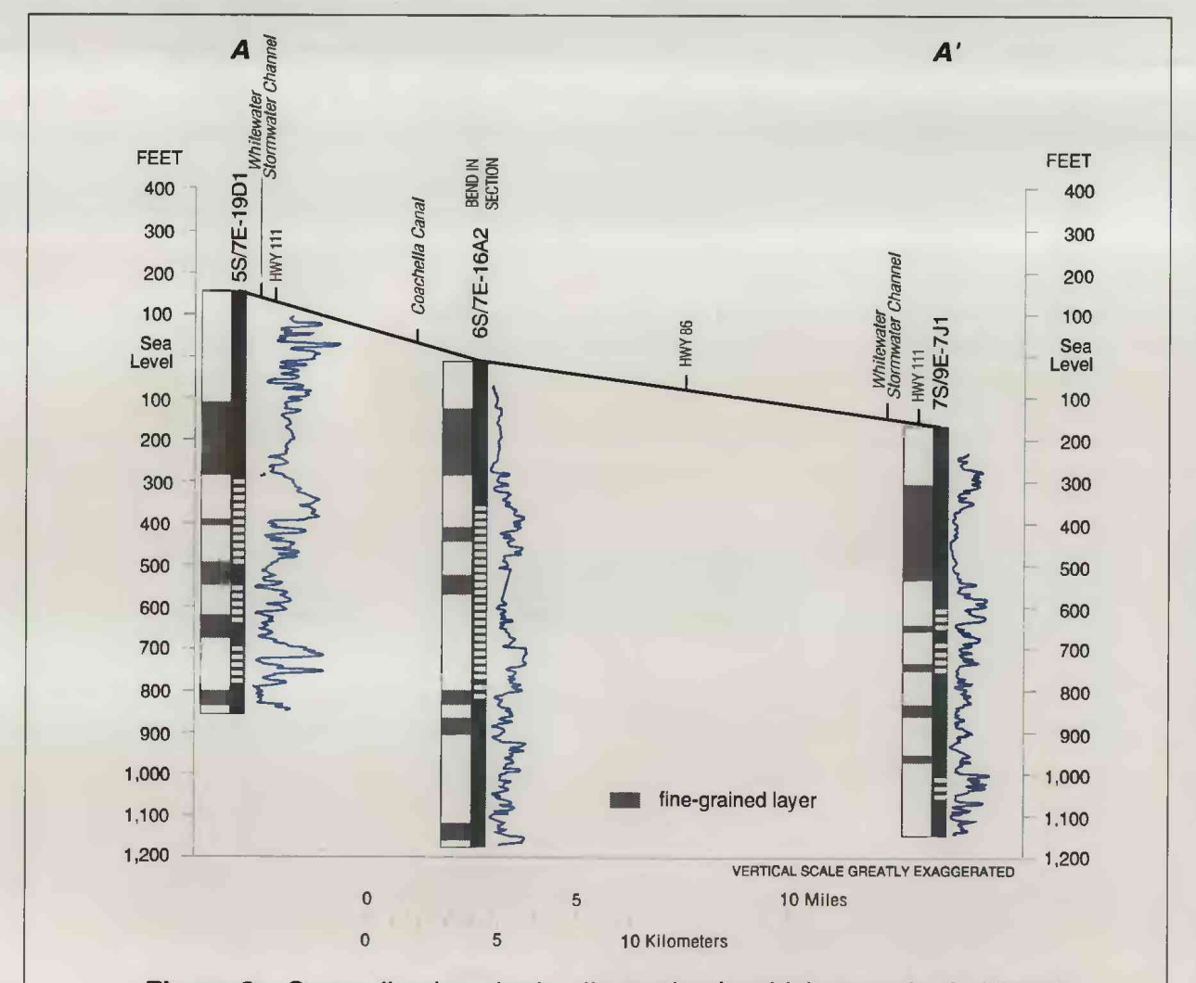


Figure 2—Generalized geohydraulic section in which grey shaded bands represent some of the thicker layers of fine-grained sediments, as interpreted from the electrical resistivity borehole logs depicted to the right of the wells. Screened intervals are indicated by thin lines in each well. (Modified from Reichard and Meadows, 1992)

Acknowledgments

The authors wish to acknowledge Steven Robbins of CVWD and members of his staff for having made available their ground-water database and electric-log data, and Tim Lystell and the staff of CVWD Surveys Unit for their assistance in providing field leveling. The willingness of Allen Christensen, Dennis Clark, Steven Gallanthine, Barry Kerr, and Daniel Kirkman of the USGS to assist in the collection of field data during the hottest days of early summer is greatly appreciated. Devin Galloway and Randy Hanson of the USGS provided valuable insights into the mechanics of aquifer-system compaction.

DESCRIPTION OF STUDY AREA

Geography

The Coachella Valley is a northwest-trending valley in southeastern California (fig. 1) that is about 65 mi long with an area of about 400 mi^2. The upper Coachella Valley is drained primarily by the Whitewater River, which becomes the channelized Whitewater Stormwater Channel that provides drainage for the lower Coachella Valley and empties into the Salton Sea (fig. 1). Land-surface elevations vary from more than 10,000 ft above sea level at the peaks of the surrounding mountains to more than 230 ft below sea level at the Salton Sea.

The land-subsidence monitoring network described in this report covers only the lower Coachella Valley. As defined in this report, the lower Coachella Valley extends from about 2 mi north of the city of Indio to the Salton Sea. The lower Coachella Valley is bounded by the upper Coachella Valley on the north, the Mecca Hills on the east, the Salton Sea on the south, and the Santa Rosa Mountains on the west. The valley floor is about 10 mi wide and 20 mi long in the northwest direction.

The climate of the lower Coachella Valley is arid desert, with an average annual rainfall of 3.15 in. Temperatures range from about 120°F in the summer on the valley floor to below 32°F in the winter in the surrounding mountains.

Geohydrology

Coachella Valley is filled with as much as 12,000 ft of sediments; the upper 2,000 ft of these sediments have been defined by California Department of Water Resources (1979) as water-bearing deposits. In this report, the water-bearing deposits are referred to as the aquifer system. The aquifer system consists of gravel, sand, silt, and clay of alluvial and lacustrine origins. Electrical-resistivity borehole logs for selected wells (fig. 2) indicate that alternating thick layers of fine-grained sediments (silt and clay) are interspersed within the aquifer system. However, because of the limited data, the distribution and continuity of these fine-grained deposits is uncertain.

Because of the lack of perennial surface-water sources in lower Coachella Valley, ground water was the predominant source for agricultural, municipal, and domestic water supplies prior to the importation of Colorado River water through the Coachella Canal in 1949. Water-level data indicate that there were declines of as much as 50 ft between the late 1920's and 1949 in some areas [wells 7S/8E-34G1 and 7S/9E-30M1 (fig. 3)]. As a result of the importation of Colorado River water to some parts of the Coachella Valley, ground-water pumping was reduced, and water levels recovered from the 1950's through the 1970's (fig. 3). Since the late 1970's, however, the demand for water has exceeded the deliveries of imported surface water, and ground-water levels generally have been declining throughout lower Coachella Valley (fig. 3) as a result of increased ground-water pumping. Ground-water levels declined by as much as 150 ft from 1949 through the late 1990's in well 7S/9E-30M1. Water levels in many areas of the lower Coachella Valley currently are lower than previously recorded levels.

MECHANICS OF LAND SUBSIDENCE

Land-subsidence is known to occur in valleys containing aquifer systems that are, in part, made up of fine-grained sediments and that have undergone extensive ground-water development. Although land subsidence has not been previously documented in the lower Coachella Valley, a large earth fissure (fig. 4) noted about 2 mi north of Lake Cahuilla in 1948 may have formed in response to land subsidence occurring during the earlier period of ground-water-level declines.

photo provided by Coachella Valley Water District

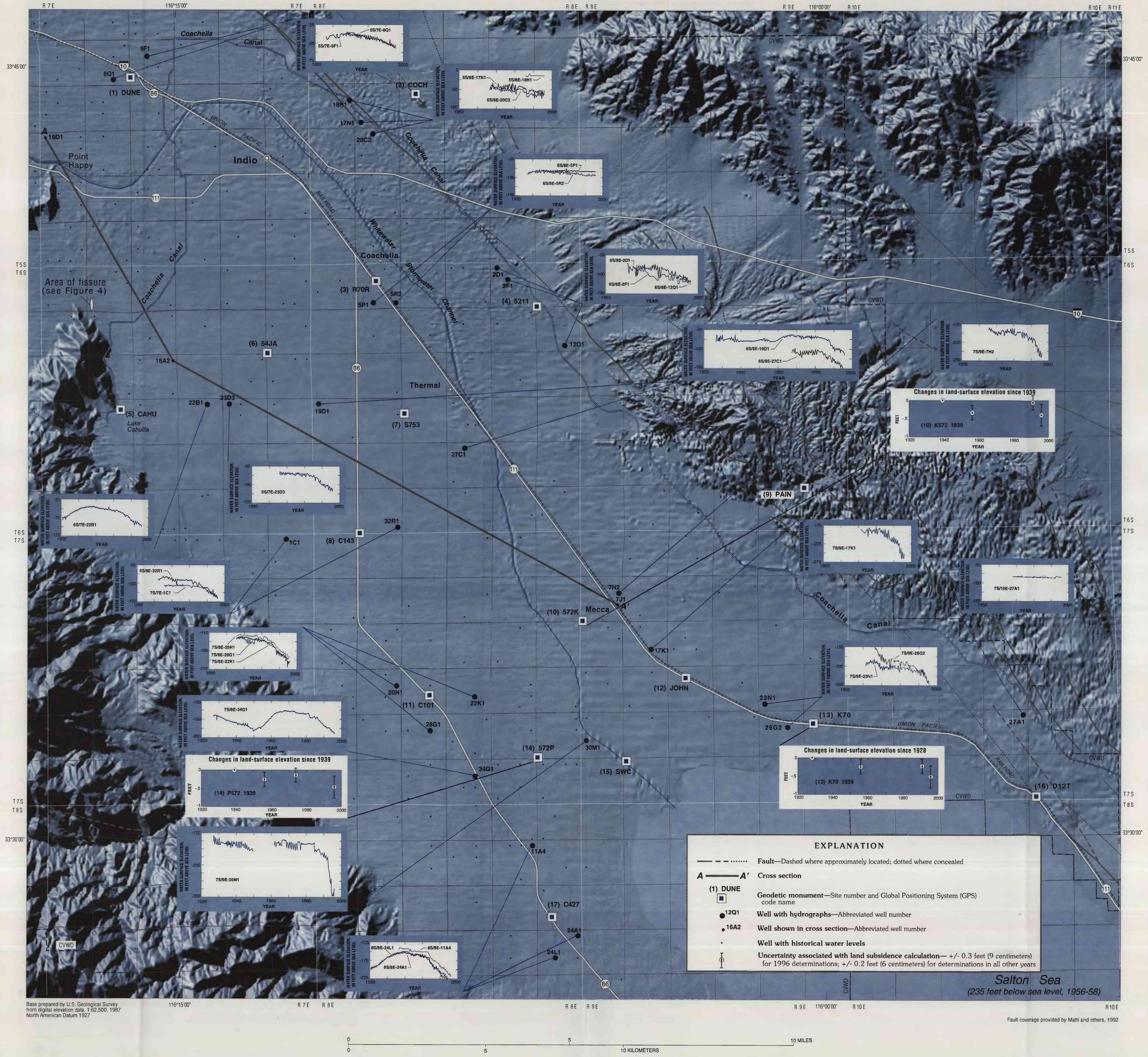
Figure 4—Fissure, possibly related to land subsidence processes, was formed on July 23, 1948, in the southwest quadrant of T6S/R7E-S5 (at Ave 52 west of Adams St).

What causes land subsidence, and how do water-level declines relate to land subsidence? The structure of a sedimentary aquifer system is supported by a combination of the skeleton of the sediment grains and the buoyancy of the ground water that fills the intergranular pore space (Meinzer, 1928). When ground water is withdrawn in quantities that result in regional water-level declines, more weight of the overlying sedimentary material must be supported solely by the skeleton. Loss of the buoyancy support increases the intergranular load, or effective stress, on the skeleton. Given an increase in effective stress, the skeleton is subject to deformation. The vertical component of this deformation sometimes results in irreversible compaction of the aquifer system and land subsidence. An aquifer-system skeleton that consists primarily of fine-grained sediments, such as silt and clay, is much more compressible than one that consists primarily of coarse-grained sediments, such as sand and gravel.

Aquifer-system deformation is elastic and reversible if the stress imposed on the skeleton is smaller than the previous maximum effective stress. The historically largest effective stress imposed on the aquifer system—usually as a result of the lowest ground-water level—is called the "preconsolidation stress." If stress imposed on the skeleton is greater than the preconsolidation stress, the pore structure of the fine-grained sediments undergoes significant rearrangement, which results in an irreversible reduction of pore volume and compaction of the aquifer system. A more complete discussion of aquifer-system compaction can be found in Poland (1984).

SUBSIDENCE MONITORING NETWORK

A land-subsidence monitoring network has been established by the USGS in the lower Coachella Valley to assess historical elevation changes and to establish a baseline measurement for future monitoring. Changes in elevation are calculated by comparing land-surface elevations measured at different times. One way to measure land-surface elevations in geographically large areas is to utilize GPS surveying. GPS is a U.S. Department of Defense satellite-based navigation system designed to provide continuous worldwide positioning and navigation capability. GPS surveying utilizes satellite and Earth-based reference station data to accurately locate and determine the elevation of geodetic monuments.



Base prepared by U.S. Geological Survey from digital elevation data, 1:62,500, 1967
North American Datum 1927

Fault coverage provided by Matti and others, 1992

Figure 3—Network of geodetic control stations for monitoring land subsidence and hydrographs of nearby ground-water wells.

Table 1—Horizontal position, vertical coordinates, and differences in land-surface elevation for geodetic network monuments in lower Coachella Valley, California
[Latitude, longitude, and ellipsoid height are referenced to the North American Datum 1983; elevation is referenced to National Geodetic Vertical Datum of 1929. Difference in elevation is calculated between 1996 and earliest leveled measurements. NA, not applicable; --, no historical elevations]

Site	Global Positioning System code name	Bench mark name	Latitude	Longitude	Adjustment 1: Elevation (feet above sea level)	Difference in elevation (feet)	Measurement interval	Period of time (years)	Adjustment 2: Ellipsoid height (meters)	Proximate well number
(1)	DUNE	DUNEPORT Azimuth	33°44'46"	116°16'10"	48.809	**-.3**	1991-96	5	-17.309	5S/7E-8Q1, -9F1
(2)	COCH	COACH 1931	33°44'25"	116°09'30"	215.203	fixed	NA	NA	33.496	5S/8E-17N1, 18H1, -20C2
(3)	R70R	R70 Reset 1958	33°40'49"	116°10'26"	-72.001	**-.2**	1956-96	40	-54.400	6S/8E-5P1, -5R2
(4)	5211	USBR 52.11	33°40'17"	116°06'43"	-.906	**-.3**	~1946-96	~50	-32.701	6S/8E-2D1, -2F1, -12Q1
(5)	CAHU	Lake Cahuilla	33°38'19"	116°16'25"	4.390	fixed	NA	NA	-30.764	6S/7E-22B1
(6)	54JA	Ave 54 and Jackson	33°39'24"	116°13'00"	-45.728	--	NA	NA	-46.358	6S/7E-23D3
(7)	S753	S753 1945	33°38'13"	116°09'49"	-116.972	**-.3**	1945-96	51	-68.230	6S/8E-19D1, -27C1
(8)	C143	Caltrans 14.3 Reset 1994	33°35'54"	116°10'52"	-129.754	--	NA	NA	-72.086	6S/8E-32R1, 7S/7E-1C1
(9)	PAIN	Painted Canyon	33°36'43"	116°00'30"	412.866	fixed	NA	NA	93.309	--
(10)	572K	K572 1939	33°34'09"	116°05'42"	-192.749	[1]**-.4**	1939-96	57	-91.568	7S/9E-7H2
(11)	C101	Caltrans 10.1 1986	33°32'44"	116°09'16"	-58.461	**.1**	1986-96	10	-50.405	7S/8E-20H1, -22K1, -28G1
(12)	JOHN	Johnson	33°33'03"	116°03'18"	-201.171	**-.3**	1991-96	5	-94.230	7S/9E-17K1
(13)	K70	K70 1928	33°32'09"	116°00'21"	-192.375	[1]**-.5**	1928-96	68	-91.587	7S/9E-23N1, -26G2
(14)	572P	P572 1939	33°31'32"	116°06'46"	-191.998	[1]**-.5**	1939-96	57	-91.339	7S/8E-34G1
(15)	SWC	Stormwater Channel	33°31'27"	116°04'42"	-221.243	**-.1**	1967-96	29	-100.364	7S/9E-30M1
(16)	D12T	D1299 Tie	33°30'42"	115°55'11"	-199.723	fixed	NA	NA	-93.798	7S/10E-27A1
(17)	C427	Caltrans 4.27 1987	33°28'25"	116°06'27"	-133.186	**.0**	1987-96	9	73.396	8S/8E-11A4, -24A1, -24L1

[1] Long-term historical changes in land-surface elevations are shown by graphs in figure 3.

Network Design

The land-subsidence monitoring network consists of permanent geodetic monuments where horizontal and vertical position can be measured accurately to assess spatial and temporal changes in land-surface elevations. Geodetic monuments are markers that are anchored to the ground or in a structure and used in precise measurements of horizontal or vertical positions or both for surveying and mapping. Historical data for bench marks in the lower Coachella Valley were compiled and reviewed to determine their geographic extent and the quality of the vertical-control data. Sources of these data include the National Geodetic Survey (NGS) (formerly the U.S. Coast and Geodetic Survey), California Department of Transportation (Caltrans), U.S. Bureau of Reclamation, and CVWD. Geodetic monuments were visited to assess whether they had been damaged or destroyed and their suitability for GPS observations. The monitoring network in lower Coachella Valley consists of 17 geodetic monuments, of which 15 have historical elevations (table 1). The spacing between bench marks meets the network design criteria (Zilkoski and Frakes, 1996) of a distance not exceeding 10 km (6.0 mi) and an average spacing not exceeding 7 km (4.2 mi).

Determination of Land-Surface Elevations and Ellipsoid Heights

GPS measurements were made with six dual-frequency, half-wavelength GPS receivers (Ashtech LD-XII and MD-XII) at the 17 geodetic monuments during the period June 3-14, 1996, to determine land-surface elevations and ellipsoid heights. In this study, land-surface elevations are referenced to the sea-level datum, National Geodetic Vertical Datum of 1929 (NGVD) so that elevations determined in the 1996 survey can be compared with historical land-surface elevations. Ellipsoid height is the vertical coordinate relative to the satellite reference system, for example, the ellipsoid that closely approximates the Earth's shape, the North American Datum of 1983 (NAD83). The difference between the two reference systems is called the geoid height, and it is about 30 m (98 ft) in Coachella Valley. Land-surface elevations determined by GPS surveying are obtained by adding geoid height to ellipsoid height. Because the geoid height is a modeled value rather than a measured value, there is less error when computing and comparing ellipsoid heights.

The GPS surveying was done in accordance with the most current edition (version 4) of "Guidelines for establishing GPS-derived ellipsoid height" at that time (Zilkoski and Frakes, 1996). There were two minor variations from the NGS guidelines. Full-wavelength GPS receivers are stipulated in the guidelines; to compensate for using half-wavelength receivers, the duration of field measurements was nearly tripled from those in the guidelines. GPS measurements were made at the 17 geodetic monuments on at least 2 different days and data were recorded for 2.5 to 3 hours during each observation period. The second variation was that single-baseline, rather than multi-baseline, processing software was used in post processing. Software used for the baseline and relative-positioning computations was GPPS version 5.0 (Ashtech), the software used for the least squares adjustments of GPS observations to local datum coordinates was FILLNET version 3.1 (Ashtech), and the model used for adjusting heights derived from the GPS-satellite datum to the NGVD29 datum was GEOID96 (NGS). During least squares adjustments, the coordinates that are considered known are specified to not change, and the observations made at noncontrol monuments are shifted so that the relative positions between monuments in the network are accurate with the least adjustment to the original measurements.

To compute land-surface elevations, four geodetic monuments in the network served as vertical control—sites 2, 5, 9, and 16 (fig. 3, table 1)—and elevations were determined for the remaining 13 monuments in Adjustment 1. The three criteria for selecting the vertical-control sites were (1) geographic distribution in the study area, (2) stable land-surface elevations, and (3) accurate previous measurements. The vertical control sites selected are in foothill areas, where ground-water pumping is minimal and land-surface elevations were assumed to be stable. The southwest part of the network has no vertical control because all of the bench marks in this area are in alluvial sediments and, therefore, could not be considered stable.

Because bench-mark candidates for vertical control in ellipsoid height adjustments do not require historical leveling measurements, a different set of bench marks was selected for Adjustment 2. Six bench marks located at the perimeters of the land-subsidence monitoring network were selected as control because of their geographic distribution; they were sites 1, 2, 5, 9, 11, and 16 (fig. 3, table 1). GPS measurements were made by the USGS at these monuments on 3 different days for 6.5 hours each day.

In Adjustment 2, the determination of ellipsoid heights for the 17 geodetic monuments in the network involved two phases of relative positioning and least squares adjustment. In the first phase, horizontal coordinates and ellipsoid heights for the six control monuments were determined by processing measurements made at these monuments with measurements made simultaneously at several Continuously Operating Reference Stations (CORS). GPS observations are recorded continuously (generally at 30-second intervals) and archived by members of the Southern California Integrated GPS Network (SCIGN) for the CORS in the area surrounding Coachella Valley. Observation data and accurate coordinates of BLYT (near Blythe), DHLG (near Durmid Hill), PIN1 (near Pinyon Flat), MONP (near Monument Peak), and CRFP (near Yucaipa) (fig. 1), and precise satellite orbital data produced by NGS were downloaded from GPS data archives. In the second phase, the coordinates of the six Coachella Valley network monuments were then considered known and held fixed during the second phase of Adjustment 2, in which positions and ellipsoid heights for the other 11 monuments were determined. The level of uncertainty for these heights is about +/- 0.07 ft (2 cm) at a 95-percent confidence level.

SUBSIDENCE DETERMINATIONS

Generally, the comparison of bench-mark elevations measured during surveys made at different times and sometimes by different agencies with various standards of accuracy and networks of various geographic scales incorporates uncertainties of at least +/- 0.2 ft (6 cm) (David Zilkoski, National Geodetic Survey, oral commun., 1996). Additionally, the error associated with elevations determined by GPS surveying could be as much as 0.1 ft (3 cm) because of inaccuracies in the GEOID96 model (Milbert, 1996). As a result of these factors and because elevations in this survey were determined using some vertical control values that were originally referenced to the North American Vertical Datum of 1988, the uncertainty of land-subsidence determinations involving 1996 elevations is at least +/- 0.3 ft (9 cm). Land-surface elevations determined in 1996 by GPS surveying were compared with elevations at 11 sites that have historical leveling data to determine the possible existence, location, and magnitude of land subsidence in the lower Coachella Valley (table 1).

With the exception of sites 11 and 17, calculated cumulative land-surface elevation changes between 1996 and the earliest measurement ranged from about -0.1 to -0.5 ft. The calculated elevation change at site 11 was +0.1 ft from 1986-96, and at site 17, no change was calculated from 1987 to 1996 (table 1). The magnitude of these land-surface elevation changes when comparing historical data and measurements made during this study is less than, or not much greater than, the range of uncertainty [+/- 0.3 ft (9 cm)] for measurements made under these conditions; therefore, they do not unequivocally indicate that there is land subsidence in lower Coachella Valley.

To assess whether a correlation between the land-surface elevation changes and the water-level history could be made, ground-water wells and bench marks that had long-term measurements were selected for analysis. Although the magnitude of the land-surface-elevation changes (for sites 10, 13, and 14; fig. 3) is not large, the fact that the timing of these changes corresponds with that of the water-level changes (at wells 7S/9E-7H2, 7S/9E-23N1 and 7S/9E-26G2, and 7S/8E-34G1 and 7S/9E-30M1; fig. 3) indicates that land subsidence resulting from ground-water withdrawal possibly is occurring, and that a significant part of the land subsidence has occurred since the early 1990's when ground-water levels began declining below previously recorded lows.

FUTURE MONITORING

Continued monitoring in lower Coachella Valley is needed because ground-water levels are continuing to decline and small amounts of land subsidence have been documented by this study. The primary benefit of the network established during this study will be for the future detection and monitoring of land subsidence in the lower Coachella Valley. By using this network and adhering to the stringent procedures for GPS surveying, a vertical accuracy of +/- 0.07 ft (2 cm) can be obtained for ellipsoid heights. Comparisons of ellipsoid heights from GPS surveying will eliminate most of the uncertainty associated with comparisons of leveled elevations. On the basis of current ground-water levels and the rate of subsidence between 1991-96, GPS surveys of the network every 2-3 years would help to detect the magnitude and extent of subsidence. The magnitude of the subsidence during this period would be expected to exceed the range of error inherent in GPS surveying methods.

In order to determine whether any detected land subsidence is related to aquifer-system compaction, it will be necessary to maintain a water-level monitoring network. Seasonal measurements that are at or near the lowest historical water level could contribute to the quantification of largest effective stresses on the aquifer system and a correlation with land-subsidence measurements. Two other methods that might facilitate land-subsidence detection and monitoring are examination of satellite-based Synthetic Aperture Radar (SAR) imagery and installation of extensometer wells. Methods have been developed to produce interferograms, which are visual depictions of a digital comparison of SAR images taken by a spacecraft in different orbits (Massonet and others, 1996; D.L. Galloway, U.S. Geological Survey, written commun., 1997). Interferograms could provide a regional perspective of changes in land-surface elevation at nearly the same resolution or accuracy as geodetic measurements. If more definitive land-subsidence assessments become necessary, an extensometer well could be installed to quantify compaction between land surface and the depth of the casing anchor.

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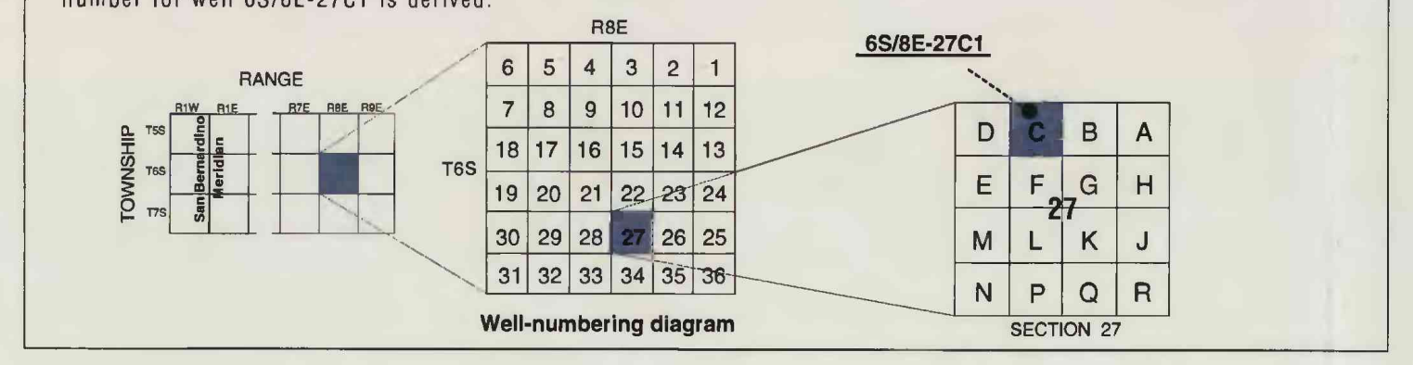
Well-Numbering System

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 boustrophedonic manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. 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 referenced to the San Bernardino base line and meridian (S). Well numbers consist of 15 characters and follow the format 006S008E27C001S. In this report, well numbers are abbreviated and written 6S/8E-27C1. Wells in the same township and range are referred to only by their section designation, 27C1. The following diagram shows how the number for well 6S/8E-27C1 is derived.



Well-numbering diagram

Conversion Factors

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
foot (ft)	30.48	centimeter (cm)
inch (in.)	2.54	centimeter (cm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)

Temperature given in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) by the following equation:

$$°F=1.8(°C)+32$$

Coordinates determined by Global Positioning System (GPS) surveying are generally reported in metric units. The industry standard for GPS usage is that field measurements and subsequent computations, including standard error determinations, are done in the metric system. However, historical land-surface elevations were measured in feet during leveling surveys. Because most of these data were measured in the inch-pound system, GPS-derived elevations were converted from the metric system so that comparisons could be made with historical elevations. The use of dual units in this report is intended to facilitate application of the data by maintaining the integrity of the original units of measurement for GPS and leveling surveying.

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