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Detection and Measurement of Land Subsidence Using Global Positioning System Surveying and Interferometric Synthetic Aperture Radar, Coachella Valley, California, 1996–2005

Scientific Investigations Report 2007–5251

U.S. Department of the Interior
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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in)
millimeter (mm)	0.03937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Rate	
meter per day (m/d)	3.281	foot per day (ft/d)
meter per year (m/yr)	3.281	foot per year (ft/yr)
millimeter per day (mm/d)	0.003281	foot per day (ft/d)
millimeter per month (mm/mo)	0.003281	foot per month (ft/mo)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
kilometer per hour (km/h)	0.6214	mile per hour (mi/h)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Vertical displacements determined by InSAR and coordinates determined by Global Positioning System (GPS) surveying generally are 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. 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 surveying.

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 Sates and Canada, formerly called Sea Level Datum of 1929.

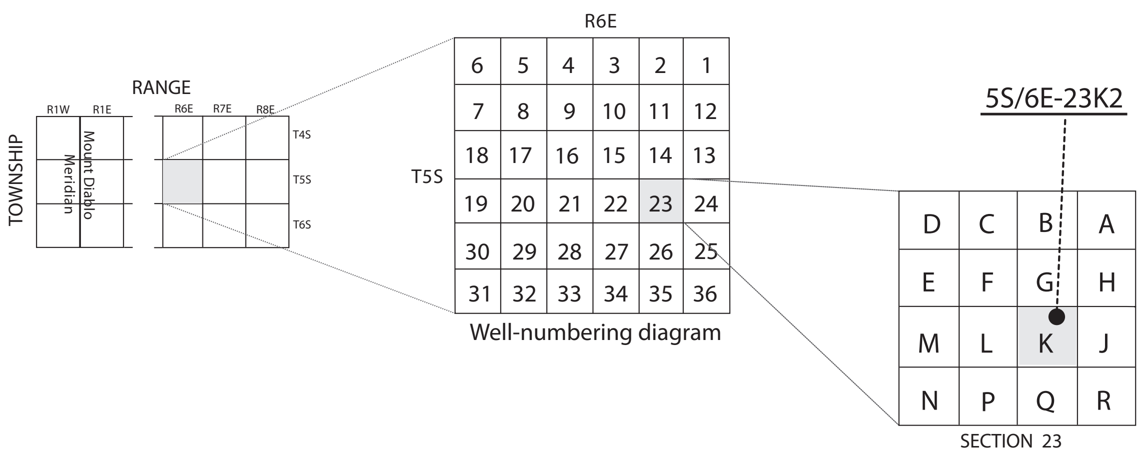
Ellipsoid heights: In this report, Global Positioning System (GPS) measurements of horizontal coordinates and ellipsoid heights are based on the North American Datum of 1983 (NAD83).

Abbreviations and Acronyms

Caltrans	California Department of Transportation
CGPS	Continuous Global Positioning System
CVWD	Coachella Valley Water District
DEM	digital elevation model
ESA	European Space Agency
GPS	Global Positioning System
IGS	International GPS Service
InSAR	Interferometric Synthetic Aperture Radar
NGS	National Geodetic Survey
SAR	Synthetic Aperture Radar
SCIGN	Southern California Integrated GPS Network
SOPAC	Scripps Orbit and Permanent Array Center
UNAVCO	University NAVSTAR (Navigation Signal Timing and Ranging) Consortium
USGS	United States Geological Survey

Well-Numbering System

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with "A" in the northeast corner of the section and progressing in a sinusoidal manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humboldt (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 005S006E23K002S. In this report, well numbers are abbreviated and written 5S/6E-23K2. Wells in the same township and range are referred to only by their section designation, 23K2. The following diagram shows how the number for well 5S/6E-23K2 is derived.



Well-numbering diagram

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Detection and Measurement of Land Subsidence Using Global Positioning System Surveying and Interferometric Synthetic Aperture Radar, Coachella Valley, California, 1996–2005

By Michelle Sneed and Justin T. Brandt

Abstract

Land subsidence associated with ground-water-level declines has been investigated by the U.S. Geological Survey in the Coachella Valley, California, since 1996. Ground water has been a major source of agricultural, municipal, and domestic supply in the valley since the early 1920s. Pumping of ground water resulted in water-level declines as large as 15 meters (50 feet) through the late 1940s. In 1949, the importation of Colorado River water to the southern Coachella Valley began, resulting in a reduction in ground-water pumping and a recovery of water levels during the 1950s through the 1970s. Since the late 1970s, demand for water in the valley has exceeded deliveries of imported surface water, resulting in increased pumping and associated ground-water-level declines and, consequently, an increase in the potential for land subsidence caused by aquifer-system compaction.

Global Positioning System (GPS) surveying and interferometric synthetic aperture radar (InSAR) methods were used to determine the location, extent, and magnitude of the vertical land-surface changes in the southern Coachella Valley. GPS measurements made at 13 geodetic monuments in 1996 and in 2005 in the southern Coachella Valley indicate that the elevation of the land surface had a net decline of 333 to 22 millimeters ±58 millimeters (1.1 to 0.07 foot ±0.19 foot) during the 9-year period. Changes at 10 of the 13 monuments exceeded the maximum uncertainty of ±58 millimeters (±0.19 foot) at the 95-percent confidence level, indicating that subsidence occurred at these monuments between June 1996 and August 2005. GPS measurements made at 20 geodetic monuments in 2000 and in 2005 indicate that the elevation of the land surface changed –312 to +25 millimeters ±42 millimeters (–1.0 to +0.08 foot ±0.14 foot) during the 5-year period. Changes at 14 of the 20 monuments exceeded the maximum uncertainty of ±42 millimeters (±0.14 foot) at the 95-percent confidence level, indicating that subsidence occurred at these monuments between August 2000 and August 2005. Eight of the fourteen monuments for which subsidence rates could be compared indicate that subsidence rates increased by as much as a factor of 10 between 2000 and 2005 compared with subsidence rates before 2000.

InSAR measurements made between May 7, 2003, and September 25, 2005, indicate that land subsidence, ranging from about 75 to 180 millimeters (0.25 to 0.59 foot), occurred in three areas of the Coachella Valley: near Palm Desert, Indian Wells, and La Quinta; the equivalent subsidence rates range from about 3 to more than 6 mm/month (0.01 to 0.02 ft/month). The subsiding areas near Palm Desert, Indian Wells, and La Quinta were previously identified using InSAR measurements for 1996–2000, which indicated that about 35 to 150 mm (0.11 to 0.49 ft) of subsidence occurred during the four-year period; the equivalent subsidence rates range from about 1 to 3 mm/month (0.003 to 0.01 ft/month). Comparison of the InSAR results indicates that subsidence rates have increased 2 to 4 times since 2000 in these three areas.

Water-level measurements made at wells near the subsiding monuments and in the three subsiding areas generally indicated that the water levels fluctuated seasonally and declined annually between 1996 and 2005; some water levels in 2005 were at the lowest levels in their recorded histories. The coincident areas of subsidence and declining water levels suggest that aquifer-system compaction may be causing subsidence. If the stresses imposed by the historically lowest water levels exceeded the preconsolidation stress, the aquifer-system compaction and associated land subsidence may be permanent. Although the localized character of the subsidence signals is typical of the type of subsidence characteristically caused by localized ground-water pumping, the subsidence may also be related to tectonic activity in the valley.

Introduction

Ground water has been a major source of agricultural, municipal, and domestic water supply in Coachella Valley, California (fig. 1), since the early 1920s. Pumping of ground water resulted in water-level declines as large as 15 m (50 ft) between the early 1920s and late 1940s. In 1949, the importation of Colorado River water through the Coachella Branch of the All-American Canal to the southern Coachella Valley began. As a result of the importation of surface water, pumping of ground water decreased in the southern Coachella Valley during the 1950s through the 1970s, and water levels in some wells in the lower valley recovered as much as 15 m (50 ft). Since the late 1970s, however, the demand for water in the southern Coachella Valley has exceeded the deliveries of imported surface water, pumping has increased, and water levels have again declined. By 2005, water levels in many wells in the southern Coachella Valley had declined 15 to 30 m (50 to 100 ft) and water levels in some wells were at their lowest recorded levels.

Declining water levels can contribute to, or induce, land subsidence in aquifer systems that consist of a significant fraction of unconsolidated fine-grained sediments (silts and clays). Ikehara and others (1997) reported that as much as 150 mm ± 90 mm (0.5 ft ± 0.3 ft) of subsidence occurred in the southern parts of the Coachella Valley between 1930 and 1996. Land subsidence can disrupt surface drainage; cause earth fissures; and damage wells, buildings, roads, and utility infrastructure. A large earth fissure was discovered in 1948 about 3 km (2 mi) north of Lake Cahuilla in La Quinta. Because subsidence had not been documented in the southern parts of the Coachella Valley prior to the report by Ikehara and others (1997), it is not known if this fissure formed in response to differential land subsidence during the earlier period (early 1920s–late 1940s) of ground-water-level declines. However, fissuring is recurring in this area (Clay Stevens, TerraPacific Consultants, Inc., written commun., 2006). Subsidence-related earth fissures and reactivated surface faults have been identified in many other ground-water basins in the western United States (Holzer, 1984).

The Coachella Valley Water District (CVWD) works cooperatively with local stakeholders to manage the water supply for a large part of the Coachella Valley (fig. 1). Because of the potential for ground-water pumping to cause land subsidence, the CVWD entered into a cooperative agreement with the U.S. Geological Survey (USGS) to monitor vertical changes in land surface to determine if land subsidence was occurring in the Coachella Valley. In 1996, the USGS, in cooperation with CVWD, established a geodetic network of monuments to monitor vertical changes in land surface in the southern Coachella Valley using Global Positioning System (GPS) surveys and to establish baseline values for comparisons with results of future surveys. The geodetic network needs to be surveyed intermittently to determine the distribution and amount of land subsidence. In addition, interferometric synthetic aperture radar (InSAR) data collected since 1996 have been used to detect and quantify land subsidence in areas removed from the geodetic monuments.

Purpose and Scope

The objectives of this study are to detect and quantify land subsidence that has occurred in the Coachella Valley from 1996 through 2005 by completing GPS surveys at the established geodetic network of monuments and by using InSAR data. This report presents the results and interpretations of GPS data collected at the monuments in the monitoring network during surveys in 1996, 1998, 2000, and 2005, and also of spatially detailed maps of vertical land-surface changes generated using InSAR data collected between 1996 and 2005. The InSAR-generated maps extend from near Palm Springs to near the Salton Sea (fig. 1). Data showing ground-water-level change during 1996–2005 were examined and compared with the GPS measurements and the InSAR-generated maps to determine if the vertical changes in land surface may be related to the changes in ground-water levels.

Description of Study Area

The Coachella Valley is a 100-km (65 mi) long, northwest-trending valley in southeastern California (fig. 1). The valley covers about 1,000 km^2 (400 mi^2) (California Department of Water Resources, 1964) and includes the cities of Cathedral City, Coachella, Desert Hot Springs, Indio, La Quinta, Palm Desert, Palm Springs, and Rancho Mirage. The valley is bordered by the San Jacinto and Santa Rosa Mountains on the west, the San Bernardino and the Little San Bernardino Mountains on the north, the Cottonwood Mountains and the Mecca Hills on the east, and the Salton Sea on the south (fig. 1). The Coachella Valley is drained primarily by the Whitewater River, which flows into the Whitewater Stormwater Channel and eventually discharges into the Salton Sea (fig. 1). Land-surface elevations vary from more than 70 m (230 ft) below sea level at the Salton Sea to more than 3,000 m (10,000 ft) above sea level at the peaks of the surrounding mountains.

The climate of the Coachella Valley floor is arid. Average annual rainfall ranges from 80 mm (3 in) on the valley floor to more than 760 mm (30 in) on the crests of the mountains to the west and north of the valley (California Department of Water Resources, 1964). Temperatures range from about 50ºC (120ºF) on the valley floor in the summer to below 0ºC (32ºF) in the surrounding mountains in the winter.

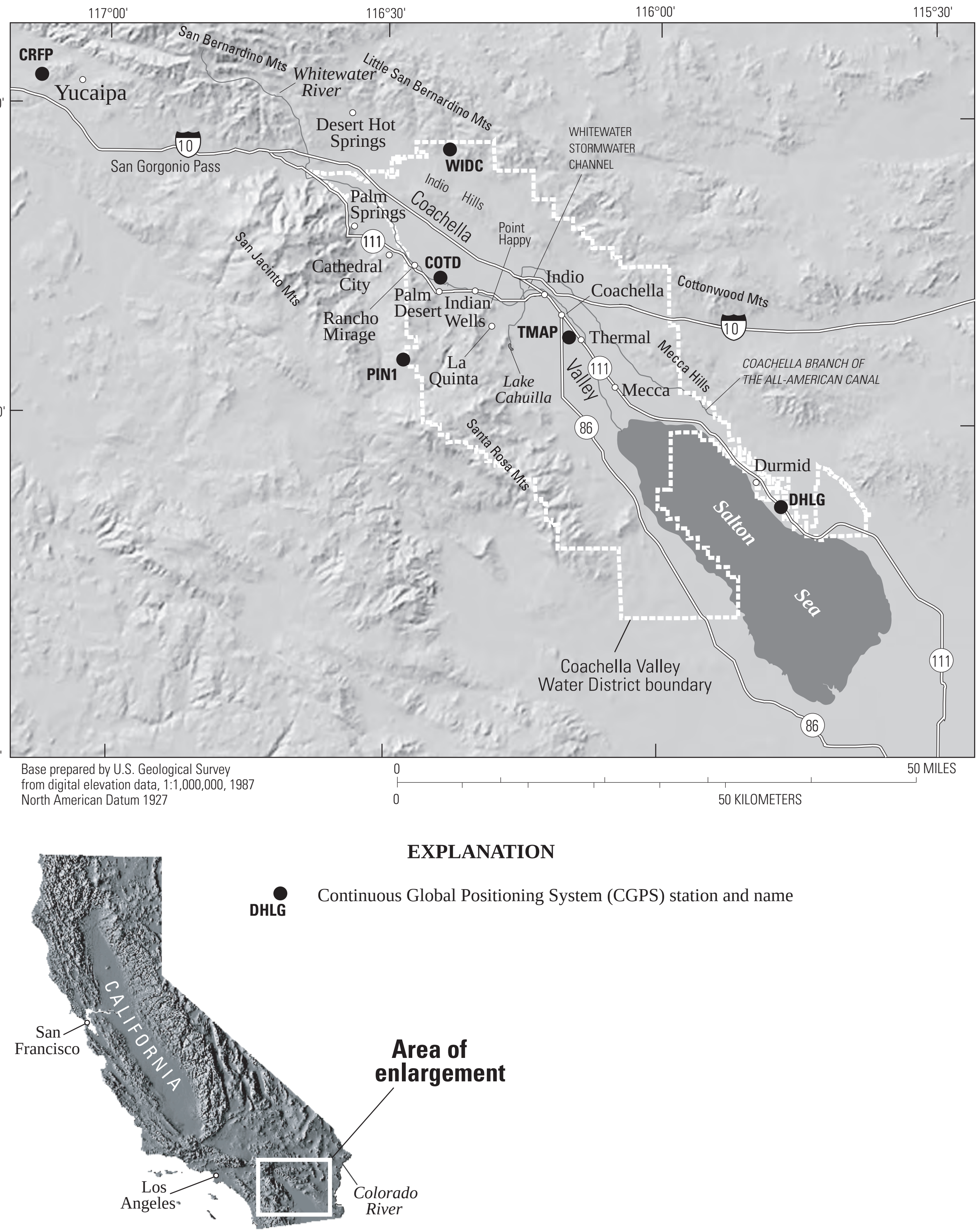


Figure 1. Map showing location of study area and of six Continuous Global Positioning System (CGPS) stations in or near Coachella Valley, California.

Previous Land-Subsidence Studies

This study is the fourth in a series of Coachella Valley land-subsidence studies that have been completed by the USGS in cooperation with CVWD. Ikehara and others (1997) documented the development of the geodetic monitoring network and areas of possible land subsidence in Coachella Valley by comparing historical leveling measurements with GPS surveying measurements made in 1996. The vertical changes in land surface between 1996 and the earliest measurements at monuments in the monitoring network do not exceed 150 mm (0.5 ft) (Ikehara and others, 1997). The range of uncertainty (±90 mm or ±0.3 ft) of these calculated vertical changes in land surface, however, is large because the historical leveling surveys were done at different times and sometimes by different agencies using different methods. Furthermore, the methods used for the leveling surveys had different standards of accuracy and the networks were of different geographic extents (Ikehara and others, 1997). Sneed and others (2001) reported that GPS measurements indicated small amounts of subsidence between 1996 and 1998 at some monuments in the monitoring network; Sneed and others (2002) reported that GPS measurements indicated most monuments were fairly stable between 1998 and 2000. Sneed and others (2001, 2002) also used InSAR to detect and quantify land subsidence throughout much of the Coachella Valley. InSAR measurements made between 1996 and 2000 indicated that as much as 150 mm (0.49 ft) of land subsidence occurred in areas near Palm Desert, Indian Wells, and La Quinta (Sneed, 2001, 2002).

Geohydrologic Setting

The Coachella Valley is the northernmost extent of the Salton Trough, which is the landward extension of a ridge/transform fault system (the East Pacific Rise) of the Gulf of California (McKibben, 1993). Near the end of the Miocene epoch, a spreading center separating the western Farallon plate from the eastern Pacific plate was obliquely subducted under the North American continent (McKibben, 1993). The modern Gulf of California and the Salton Trough formed about 12 million years ago during a period when subduction ceased and when the formation of an inland belt of east-west extension, alkali basalt volcanism, and crustal-spreading-induced subsidence and basin sedimentation began (McKibben, 1993). Prior to about 6 million years ago, the shear zone constituting the principal tectonic boundary between the Pacific and North American plates appears to have shifted about 250 km (155 mi) inland into this belt, initiating the formation of the modern Gulf of California and the Salton Trough (McKibben, 1993). As the Salton Trough opened, it was filled with sediment from the delta of the Colorado River. The river has been building its delta from the east into the trough since about 5 million years ago, and sedimentation has apparently kept pace with the crustal-spreading induced subsidence (McKibben, 1993). The relation between subsidence that has occurred on a geologic time scale, and vertical land-subsidence changes measured during this study are unknown.

The Coachella Valley is filled with as much as 3,700 m (12,000 ft) of sediments; the upper 610 m (2,000 ft) are water-bearing (California Department of Water Resources, 1979). In this report, the water-bearing deposits are referred to as the aquifer system, which consists of a complex unconsolidated to partly consolidated assemblage of gravel, sand, silt, and clay of alluvial and lacustrine origins (fig. 2). Sediments tend to be finer grained (contain more silt and clay) in the southern part of the valley than in the northern part because of the greater depositional distance from mountain runoff and from lacustrine deposition from ancient Lake Cahuilla. In the southern Coachella Valley, the aquifer system consists of, from top to bottom: a semiperched zone that is fairly persistent southeast of Indio; an upper aquifer; a confining layer; and a lower aquifer (California Department of Water Resources, 1964, 1979).

The near-surface semiperched zone overlies the upper aquifer southeast of Indio and consists of silts, clays, and fine sand. The semiperched zone is as much as 30 m (100 ft) thick and generally is an effective barrier to deep percolation (California Department of Water Resources, 1964, 1979). The upper aquifer is present throughout the Coachella Valley and consists of unconsolidated and partly consolidated silty sands and gravels with interbeds of silt and clay. In general, the upper aquifer is 45 to 90 m (150 to 300 ft) thick. The aquifer is unconfined except where it is overlain by the semiperched zone, southeast of Indio. In the southern Coachella Valley, the upper aquifer is separated from the lower aquifer by a confining layer of silt and clay that is 30 to 60 m (100 to 200 ft) thick. The lower aquifer is the most productive source of ground water in the southern Coachella Valley; it consists of unconsolidated and partly consolidated silty sands and gravels with interbeds of silt and clay. The top of the lower aquifer is about 90 to 180 m (300 to 600 ft) below land surface. Available data indicate that the lower aquifer is at least 150 m (500 ft) thick and may be as much as 600 m (2,000 ft) thick (California Department of Water Resources, 1964, 1979).

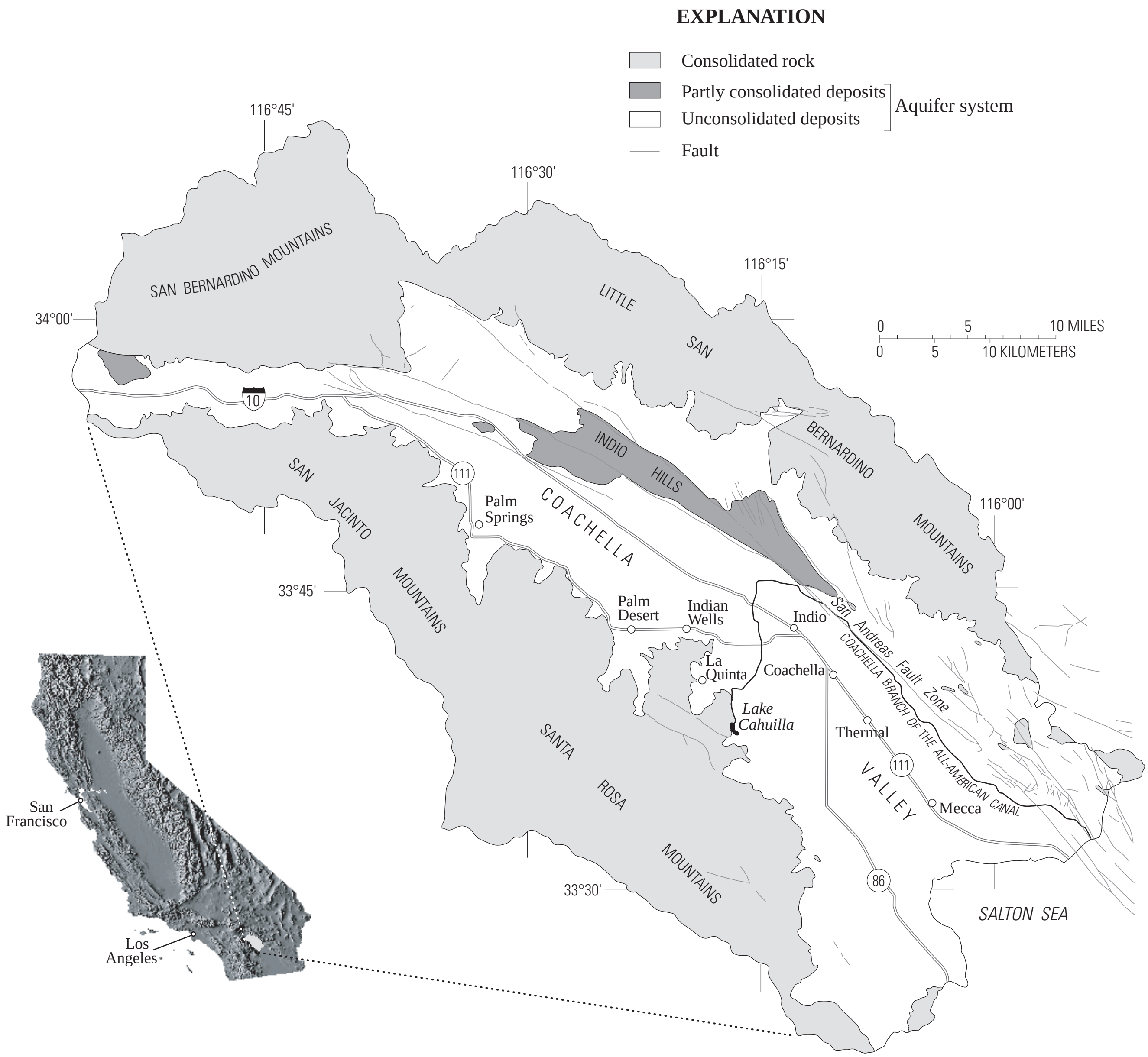


Figure 2. Map showing generalized geology of the Coachella Valley, California.

Geologic structures in the Coachella Valley have a marked influence on the occurrence and movement of ground water. The principal structural features of Coachella Valley are faults and fault-related drag and compressional folds. The most notable fault system is the northwest-trending San Andreas Fault Zone that flanks the eastern side of the valley (fig. 2). Although movement within the San Andreas Fault Zone is predominantly right lateral (across the fault, movement is to the right), vertical displacement has downdropped the southwest block (California Department of Water Resources, 1964). The faults have either juxtaposed consolidated rocks against partly consolidated or unconsolidated water-bearing deposits or displaced preferential flow paths in the partly consolidated or unconsolidated water-bearing deposits. This juxtaposition and displacement, in conjunction with cementation, compaction, and extreme deformation of water-bearing deposits adjacent to faults, can create low-permeability zones that can act as barriers to ground-water flow.

Mechanics of Pumping-Induced Land Subsidence

Land subsidence is known to occur in valleys containing aquifer systems that are, at least in part, made up of fine-grained sediments and that have undergone extensive ground-water development. The pore structure of a sedimentary aquifer system is supported by the granular skeleton of the aquifer system and the pore-fluid pressure of the ground water that fills the intergranular pore space (Meinzer, 1928). When ground water is withdrawn in quantities that result in reduced pore-fluid pressures and water-level declines, the reduction of the pore-fluid-pressure support increases the intergranular stress, or effective stress, on the skeleton. A change in effective stress deforms the skeleton—an increase in effective stress compresses it and a decrease in effective stress causes it to expand. The vertical component of this compression sometimes results in nonrecoverable compaction of the aquifer system and land subsidence. An aquifer-system skeleton that primarily consists of fine-grained sediments, such as silt and clay, is much more compressible than one that primarily consists of coarse-grained sediments, such as sand and gravel. Inelastic (nonrecoverable) compaction of coarse-grained sediment is negligible.

Aquifer-system deformation is elastic (recoverable) if the effective stress imposed on the skeleton is smaller than any previous effective stress (Leake and Prudic, 1991). The largest historical effective stress imposed on an aquifer system—sometimes as a result of the lowest ground-water level—is the “preconsolidation stress.” If a stress imposed on the skeleton is greater than the preconsolidation stress, the pore structure of the granular matrix of the fine-grained sediments is rearranged; this new configuration results in a reduction of pore volume and, thus, inelastic (largely irreversible) compaction of the aquifer system. Furthermore, the compressibility of the fine-grained sediments, and any resulting compaction under stresses greater than the preconsolidation stress, are 20 to more than 100 times greater than they are under stresses less than the preconsolidation stress (Riley, 1998).

For an aquifer-system skeleton that contains an appreciable thickness of fine-grained sediments, a significant part of the total compaction may be residual compaction (delayed compaction that occurs in thick fine-grained interbeds and confining layers while heads equilibrate with heads in the adjacent aquifers [Terzaghi, 1925]). Depending on the thickness and the vertical hydraulic diffusivity of a confining layer, pressure equilibration—and thus compaction—lags behind pressure, or head, changes in the adjacent aquifers. For a more complete description of aquifer-system compaction, see Poland (1984), and for a review and selected case studies of land subsidence caused by aquifer-system compaction in the United States, see Galloway and others (1999).

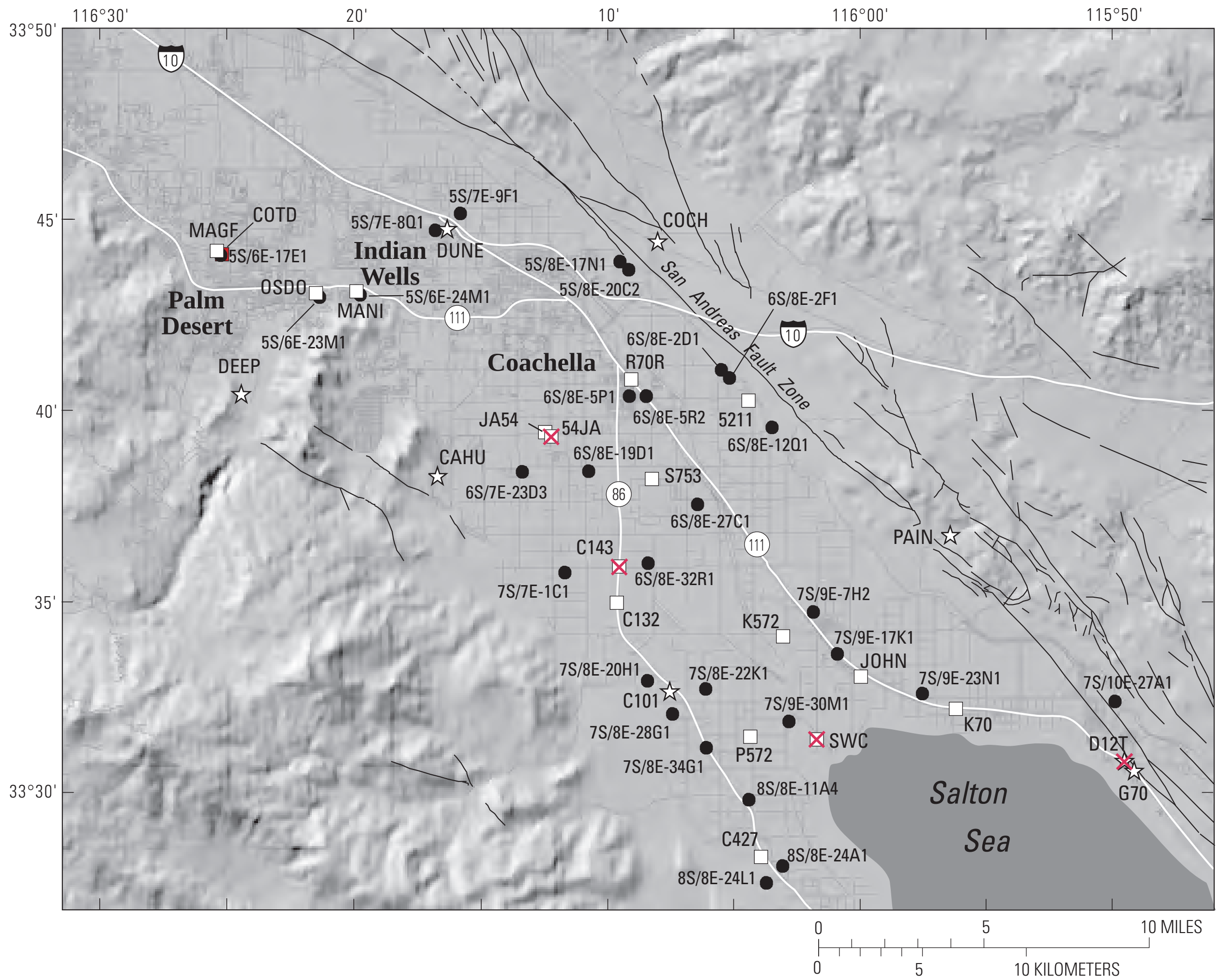
Global Positioning System (GPS) Surveys

GPS is a U.S. Department of Defense satellite-based navigation system designed to provide continuous worldwide positioning and navigation capability. For this study, GPS surveys were done to determine the three-dimensional position of monuments in the geodetic monitoring network. The network was established in 1996 by the USGS to determine changes in land-surface elevations in the network (Ikehara and others, 1997) and to establish baseline values for comparisons with results of future surveys.

Land-Subsidence Monitoring Network

The geodetic monitoring network, henceforth referred to as the land-subsidence monitoring network, consists of geodetic monuments used as GPS stations (fig. 3). Most geodetic monuments are flat metal disks that are anchored in the ground or to a structure and that can be used in making repeated surveying measurements of horizontal and (or) vertical positions. During the 1996 study by Ikehara and others (1997), historical data for monuments in the southern Coachella Valley were compiled and reviewed to determine the location and the quality of the vertical-control data. Sources of the data include NOAA’s (National Oceanic and Atmospheric Administration) National Geodetic Survey (NGS [formerly the U.S. Coast and Geodetic Survey]), the California Department of Transportation (Caltrans), the U.S. Bureau of Reclamation, and the CVWD (Ikehara and others, 1997). The geodetic monuments were examined before each of the GPS surveys in 1996, 1998, 2000, and 2005 to determine whether any had been damaged or destroyed and to evaluate their suitability for GPS observations.

The original subsidence monitoring network in the southern Coachella Valley was established in 1996 and consisted of 17 geodetic monuments. The network was modified for the 1998 GPS survey by replacing two monuments that had been destroyed (D1299 Tie [D12T] and Caltrans 14.3 Reset 1994 [C143]) with two nearby monuments (G70 1928 [G70] and Caltrans 13.2 1986 [C132]) (fig. 3). The network was again modified for the 2000 GPS survey because monument 54JA was horizontally unstable; the replacement monument (JA54) was installed about 6 m (20 ft) northwest of monument 54JA (fig. 3). In addition, four new monuments—MAGF, MANI, OSDO, and DEEP—were constructed and added in the Palm Desert and Indian Wells areas for the 2000 GPS survey (fig. 3) because the InSAR maps processed for 1996–2000 showed subsidence in these areas (Sneed and others, 2001, 2002). The monument SWC was destroyed by flooding in the Whitewater Stormwater Channel in early 2005, and thus could not be included in the 2005 survey (fig. 3). The spacing between the monuments meets the generalized network design criterion established by Zilkoski and others (1997), which requires that the distance between local network points not exceed 10 km (6 mi).



EXPLANATION

Geodetic monuments

C427 — GPS station and identifier

54JA — Destroyed or abandoned GPS station and identifier

C101 — GPS control station for one or more of the GPS surveys

D12T — Destroyed GPS control station and identifier

COTD — Continuous Global Positioning System (CGPS) station and identifier

8S/8E-24L1 — **Well and identifier**

Figure 3. Map showing network of Global Positioning System (GPS) stations and wells used to monitor vertical changes in land surface and ground-water levels, respectively, in the southern Coachella Valley, California.

Determination of Ellipsoid Heights

GPS measurements were made at the geodetic monuments to determine their horizontal positions and ellipsoid heights. Ellipsoid height is the vertical coordinate relative to a geodetically defined reference ellipse; the ellipsoid that closely approximates the Earth's shape in the study area is the North American Datum of 1983 (NAD83). To determine changes in ellipsoid heights, the heights from successive GPS surveys are compared; then, the differences in the heights are used to determine the location and magnitude of any vertical land-surface changes. The GPS surveying in 1996, 1998, 2000, and 2005 was done in accordance with "Guidelines for Establishing GPS-Derived Ellipsoid Height" by Zilkoski and others (1997) with one minor variation common to all 4 GPS surveys: single baseline, rather than multi-baseline, processing software was used for postprocessing. There are no known conclusive tests that objectively evaluate the effect of using single-baseline, rather than multi-baseline, processing software (Craymer and Beck, 1992). Other variations to the guidelines are specific to particular surveys and are described in the following sections. All of the GPS survey data were recomputed during this current study to eliminate the effects of variable processing methodologies used by assorted software and to standardize processing procedures for an improved comparison of three-dimensional positions derived from data collected during each GPS survey. Software used for the baseline and least-squares adjustment computations was Trimble Geomatics Office version 1.63.

1996 GPS Survey

GPS measurements for the 1996 survey were made using six dual-frequency, half-wavelength P-code GPS receivers (Ashtech LD-XII and Ashtech MD-XII) and choke-ring antennas (Dorne-Margolin) at the 17 geodetic monuments between June 3 and 14, 1996, to determine horizontal positions and ellipsoid heights (Ikehara and others, 1997). For this survey, the duration of the GPS measurements was nearly tripled compared with the duration specified by Zilkoski and others (1997) to compensate for using half-wavelength GPS receivers rather than the full-wavelength GPS receivers (Ikehara and others, 1997). GPS measurements were made at the 17 geodetic monuments on at least 2 different days, and data were recorded during 2.5- to 3-hour observation periods (Ikehara and others, 1997). Six of the 17 geodetic monuments—C101, CAHU, COCH, PAIN, D12T, and DUNE (fig. 3)—also were network control stations; GPS measurements were made at these six stations on 3 additional days, and data were recorded during 6-hour observation periods.

Determining the ellipsoid heights of the 17 geodetic monuments in the network involved two phases of least-squares adjustments. During the first phase of least-squares adjustments, the horizontal coordinates and ellipsoid heights for the six Coachella Valley network control monuments were determined by processing the GPS measurements made at these monuments with measurements made simultaneously at three Continuous Global Positioning System (CGPS) stations (DHLG, PIN1, and CRFP) in southern California (fig. 1), and by using precise satellite orbital data and accurate coordinates of the CGPS stations produced by the International GPS Service (IGS) and the Scripps Orbit and Permanent Array Center (SOPAC), respectively. The GPS observations of the CGPS stations were recorded continually (at 30-second intervals), and were archived by SOPAC, a member of the Southern California Integrated GPS network (SCIGN). The network control monuments were selected on the basis of geographic distribution; they are at the perimeters of the monitoring network. During the second phase of least-squares adjustments, the positions of the six Coachella Valley network control monuments were held fixed at the positions determined during the first phase, and the horizontal coordinates and ellipsoid heights for the other 11 monuments were determined. The level of uncertainty for these heights is ±50 mm (±0.16 ft) at the 95-percent confidence level.

1998 GPS Survey

GPS measurements for the 1998 survey were made using five dual-frequency, full-wavelength P-code GPS receivers (Ashtech MD-XII) and choke-ring antennas (Dorne-Margolin) at the 17 geodetic monuments between October 5 and 9, 1998, to determine horizontal positions and ellipsoid heights. GPS measurements were made at the 17 geodetic monuments on at least 2 different days, and data were recorded during 45-minute observation periods. Five of the 17 geodetic monuments—COCH, CAHU, PAIN, C101, and G70 (fig. 3)—also were network control stations; GPS measurements were made at these five stations on 3 additional days, and data were recorded during 4.5-hour observation periods.

Determining the ellipsoid heights of the 17 geodetic monuments in the network involved two phases of least-squares adjustments. During the first phase of least-squares adjustments, horizontal coordinates and ellipsoid heights for the five Coachella Valley network control monuments were determined by processing the GPS measurements made at these monuments using measurements made simultaneously at three CGPS stations (DHLG, PIN1, and WIDC) in southern California (fig. 1), and by using precise satellite orbital data and accurate coordinates of the CGPS stations produced by IGS and SOPAC, respectively. The GPS observations of the CGPS stations were recorded continually (at 30-second intervals) and were archived by SOPAC. During the second phase of least-squares adjustments, the positions of the five Coachella Valley network control monuments were held fixed at the positions determined during the first phase, and the horizontal coordinates and ellipsoid heights for the other 12 monuments were determined. The level of uncertainty for these heights is ±20 mm (±0.07 ft) at a 95-percent confidence level.

2000 GPS Survey

GPS measurements for the 2000 survey were made using six dual-frequency, full-wavelength, P-code GPS receivers (5 Trimble 4000SSIs and 1 Trimble 4000SSE) and compact L1/L2 Trimble antennas (with ground plane) at the 21 geodetic monuments between August 28 and September 1, 2000, to determine horizontal positions and ellipsoid heights. GPS measurements were made at the monuments on at least 2 different days, and data were recorded during 35-minute observation periods. Six of the 21 geodetic monuments were used as network control stations—COCH, DEEP, CAHU, PAIN, C101, and G70 (fig. 3). GPS measurements were made at these six stations on 3 additional days, and data were recorded during 5-hour observation periods.

Determining the ellipsoid heights of the 21 geodetic monuments in the network involved two phases of least-squares adjustments. During the first phase of least-squares adjustments, horizontal coordinates and ellipsoid heights of the six Coachella Valley network control monuments were determined by processing the GPS measurements made at these monuments with measurements made simultaneously at the same three CGPS stations (DHLG, PIN1, and WIDC) used in processing the 1998 GPS survey data (fig. 1), and by using precise satellite orbital data and accurate coordinates of the CGPS stations produced by IGS and SOPAC, respectively. The GPS observation frequency of the CGPS stations was set at 30 seconds, and the observations were archived by SOPAC. During the second phase of least-squares adjustments, the positions of the six network control monuments were held fixed at the positions determined during the first phase, and the horizontal coordinates and ellipsoid heights for the other 15 monuments were determined. The accuracy of these ellipsoid heights is ±30 mm (±0.10 ft) at the 95-percent confidence level.

2005 GPS Survey

GPS measurements for the 2005 survey were made using six dual-frequency, full-wavelength, P-code GPS receivers (Topcon GB1000) and compact antennas (with ground plane) (Topcon PG-A1 Geodetic) at the 20 geodetic monuments between August 15 and 19, 2005, to determine horizontal positions and ellipsoid heights. GPS measurements were made at the monuments on at least 2 different days, and data were recorded during 1-hour observation periods. Six of the 21 geodetic monuments were used as network control stations—COCH, DEEP, CAHU, PAIN, C101, and G70 (fig. 3); GPS measurements were made at these six stations on 3 additional days, and data were recorded during 6.5-hour observation periods.

Determining the ellipsoid heights of the 20 geodetic monuments in the network involved two phases of least-squares adjustments. During the first phase of least-squares adjustments, horizontal coordinates and ellipsoid heights of the six Coachella Valley network control monuments were determined by processing the GPS measurements made at these monuments using measurements made simultaneously at the same three CGPS stations (DHLG, PIN1, and WIDC) used in processing both the 1998 and 2000 GPS survey data, and by using precise satellite orbital data and accurate coordinates of the CGPS stations produced by IGS and SOPAC, respectively. The GPS observation frequency of the CGPS stations was set at 30 seconds, and the observations were archived by SOPAC. During the second phase of least-squares adjustments, the positions of the six network control monuments were held fixed at the positions determined during the first phase, and the horizontal coordinates and ellipsoid heights for the other 14 monuments were determined. The accuracy of these ellipsoid heights is ±30 mm (±0.10 ft) at the 95-percent confidence level.

GPS Results

The horizontal coordinates and the ellipsoid heights of the monuments determined from each of the four GPS surveys were compared to determine the magnitude of horizontal and vertical land-surface changes at the monuments, respectively. The horizontal changes at the monuments were consistent with the northwest movement of the Pacific Plate (with respect to the North American plate) (Shen, Z.-K. and others, 2003). The ellipsoid heights are given in table 1, and ellipsoid-height changes, adjusted to show ellipsoid height values relative to the first GPS measurement for a particular monument (that is, the first measurement was set to equal 0), are given in table 1 and shown in figure 4A.

Comparison of GPS measurements made at the 13 geodetic monuments surveyed in 1996 and in 2005 in the southern Coachella Valley indicate that the elevation of the land surface had a net decline of 333 to 22 mm ±58 mm (1.1 to 0.07 ft ± 0.19 ft) during the 9-year period (table 1). Changes at 10 of the 13 monuments (DUNE, COCH, R70R, 5211, CAHU, S753, K572, C101, K70, and C427) exceeded the maximum uncertainty of ±58 mm (±0.19 ft) at the 95-percent confidence level, indicating that subsidence occurred at these monuments between June 1996 and August 2005. Changes at 3 of the 13 monuments (PAIN, JOHN, and P572) did not exceed the maximum uncertainty of ±58 mm (±0.19 ft) at the 95-percent confidence level indicating that the vertical positions of these monuments were similar in June 1996 and in August 2005.

Table 1. Horizontal positions and ellipsoid heights for 1996, 1998, 2000, and 2005, and ellipsoid-height changes relative to the first measurement of geodetic monuments in the Coachella Valley, California.

[Latitude, longitude, and ellipsoid height are referenced to the North American Datum of 1983. Negative values for ellipsoid–height change indicate subsidence. m, meter, mm, millimeter; ft, foot; —, no data]

GPS Station	Monument name	Latitude	Longitude	Ellipsoid height (m)				Ellipsoid-height change from 1st measurement (mm)				Ellipsoid-height change from 1st measurement (ft)			
				1996 (±0.05 m)	1998 (±0.02 m)	2000 (±0.03 m)	2005 (±0.03 m)	1996	1998	2000	2005	1996	1998	2000	2005
DUNE	DUNEPORT Azimuth	33°44’46”	116°16’10”	–17.354	–17.371	–17.407	–17.687	0	–17	–53	–333	0	–0.056	–0.174	–1.093
COCH	COACH 1931	33°44’25”	116°09’30”	33.427	33.436	33.367	33.212	0	9	–60	–215	0	0.030	–0.197	–0.705
MAGF	Magnesium Falls Drive	33°44’11”	116°23’27”	—	—	27.742	27.606	—	—	0	–136	—	—	0	–0.446
MANI	Manitou Drive	33°43’11”	116°19’03”	—	—	2.962	2.884	—	—	0	–78	—	—	0	–0.256
OSDO	Osage Trail/ElDorado Drive	33°43’06”	116°20’19”	—	—	13.484	13.281	—	—	0	–203	—	—	0	–0.666
R70R	R70 Reset 1958	33°40’49”	116°10’26”	–54.402	–54.433	–54.471	–54.585	0	–31	–69	–183	0	–0.102	–0.226	–0.600
DEEP	Deep Canyon	33°40’21”	116°22’34”	—	—	190.409	190.193	—	—	0	–216	—	—	0	–0.709
5211	USBR 52.11	33°40’17”	116°06’43”	–32.682	–32.698	–32.740	–32.822	0	–16	–58	–140	0	–0.052	–0.190	–0.459
54JA	Ave 54 and Jackson (old)	33°39’24”	116°13’00”	–46.348	–46.392	—	—	0	–44	—	—	0	–0.144	—	—
JA54	Jackson and Ave 54 (new)	33°39’24”	116°13’00”	—	—	–46.907	–47.219	—	—	0	–312	—	—	0	–1.024
CAHU	Lake Cahuilla	33°38’19”	116°16’25”	–30.738	–30.778	–30.815	–31.025	0	–40	–77	–287	0	–0.131	–0.253	–0.942
S753	S753 1945	33°38’13”	116°09’49”	–68.190	–68.231	–68.276	–68.292	0	–41	–86	–102	0	–0.135	–0.282	–0.335
PAIN	Painted Canyon	33°36’43”	116°00’30”	93.365	93.352	93.318	93.343	0	–13	–47	–22	0	–0.043	–0.154	–0.072
C143	Caltrans 14.3 reset 1994	33°35’54”	116°10’52”	–72.025	—	—	—	0	—	—	—	0	—	—	—
C132	Caltrans 13.2 1986	33°34’59”	116°10’54”	—	–74.001	–74.043	–74.260	—	0	–42	–259	—	0	–0.138	–0.850
K572	K572 1939	33°34’09”	116°05’42”	–91.484	–91.515	–91.523	–91.745	0	–31	–39	–261	0	–0.102	–0.128	–0.856
JOHN	Johnson	33°33’03”	116°03’18”	–94.146	–94.158	–94.170	–94.173	0	–12	–24	–27	0	–0.039	–0.079	–0.089
C101	Caltrans 10.1 1986	33°32’44”	116°09’16”	–50.336	–50.396	–50.419	–50.431	0	–60	–83	–95	0	–0.197	–0.272	–0.312
K70	K70 1928	33°32’09”	116°00’21”	–91.483	–91.507	–91.536	–91.715	0	–24	–53	–232	0	–0.079	–0.174	–0.761
P572	P572 1939	33°31’32”	116°06’46”	–91.233	–91.259	–91.283	–91.285	0	–26	–50	–52	0	–0.085	–0.164	–0.171
SWC	Stormwater Channel	33°31’27”	116°04’42”	–100.250	–100.280	–100.300	—	0	–30	–50	—	0	–0.098	–0.164	—
D12T	D1299 Tie	33°30’42”	115°55’11”	–93.664	—	—	—	0	—	—	—	0	—	—	—
G70	G70 1928	33°30’27”	115°54’51”	—	–93.078	–93.111	–93.103	—	0	–33	–25	—	0	–0.108	–0.082
C427	Caltrans 4.27 1987	33°28’25”	116°06’27”	–73.183	–73.323	–73.272	–73.466	0	–140	–89	–283	0	–0.459	–0.292	–0.929

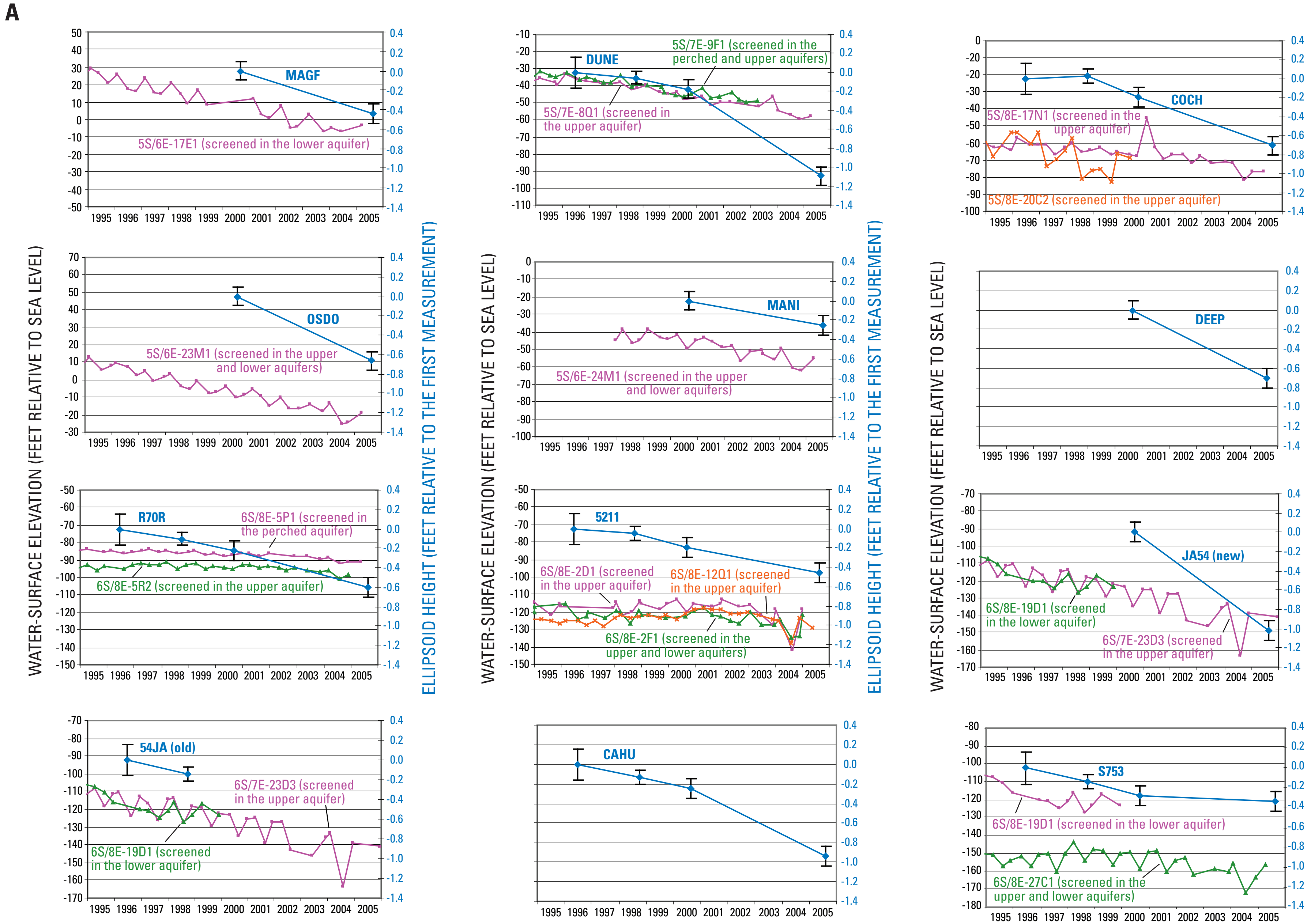
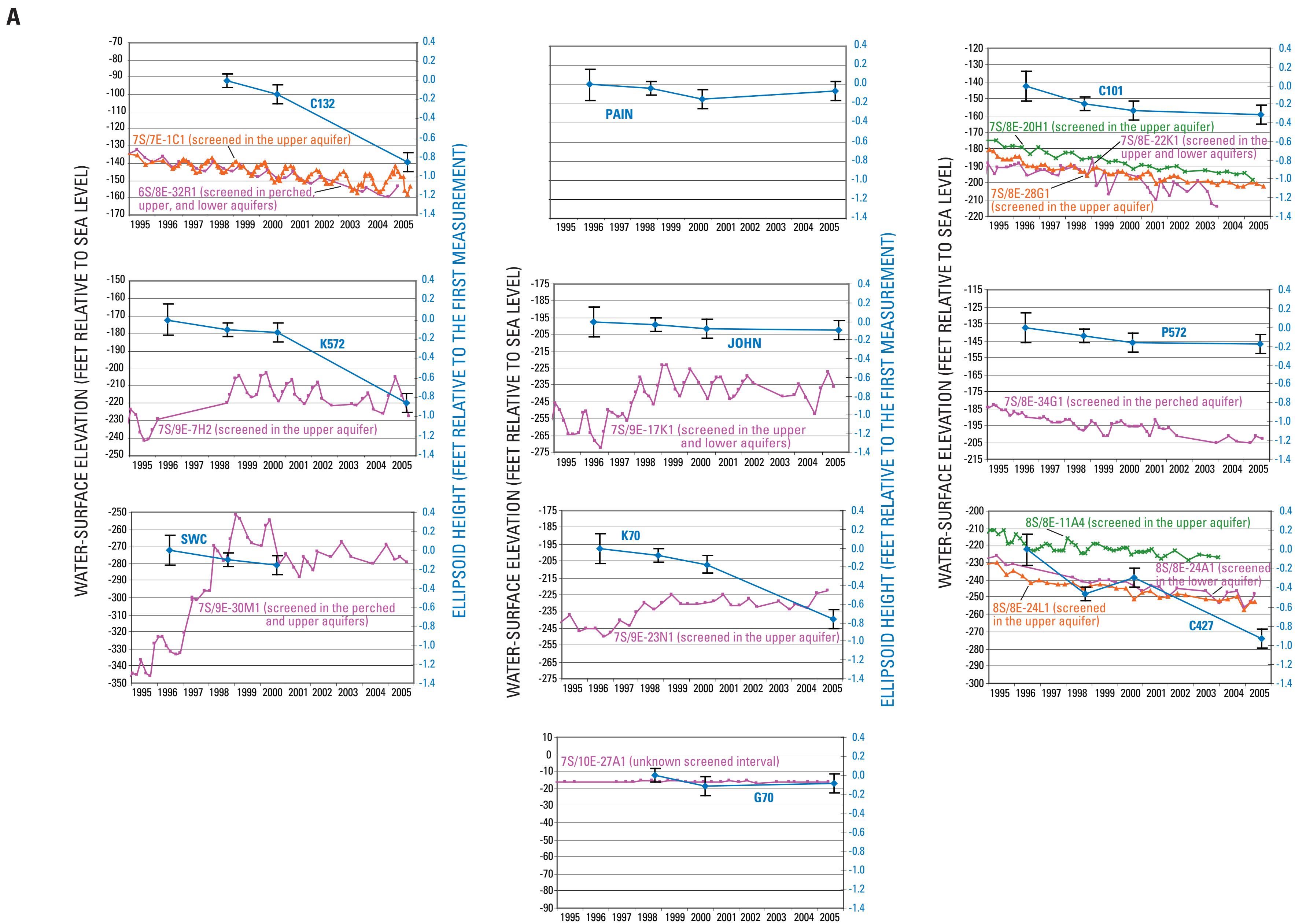


Figure 4. Hydrographs showing (A) water-surface elevations for selected wells (between 1995 and 2005), and ellipsoid-height changes (relative to the first measurement) for geodetic monuments measured at least twice, and (B) water-surface elevations for a subset of the



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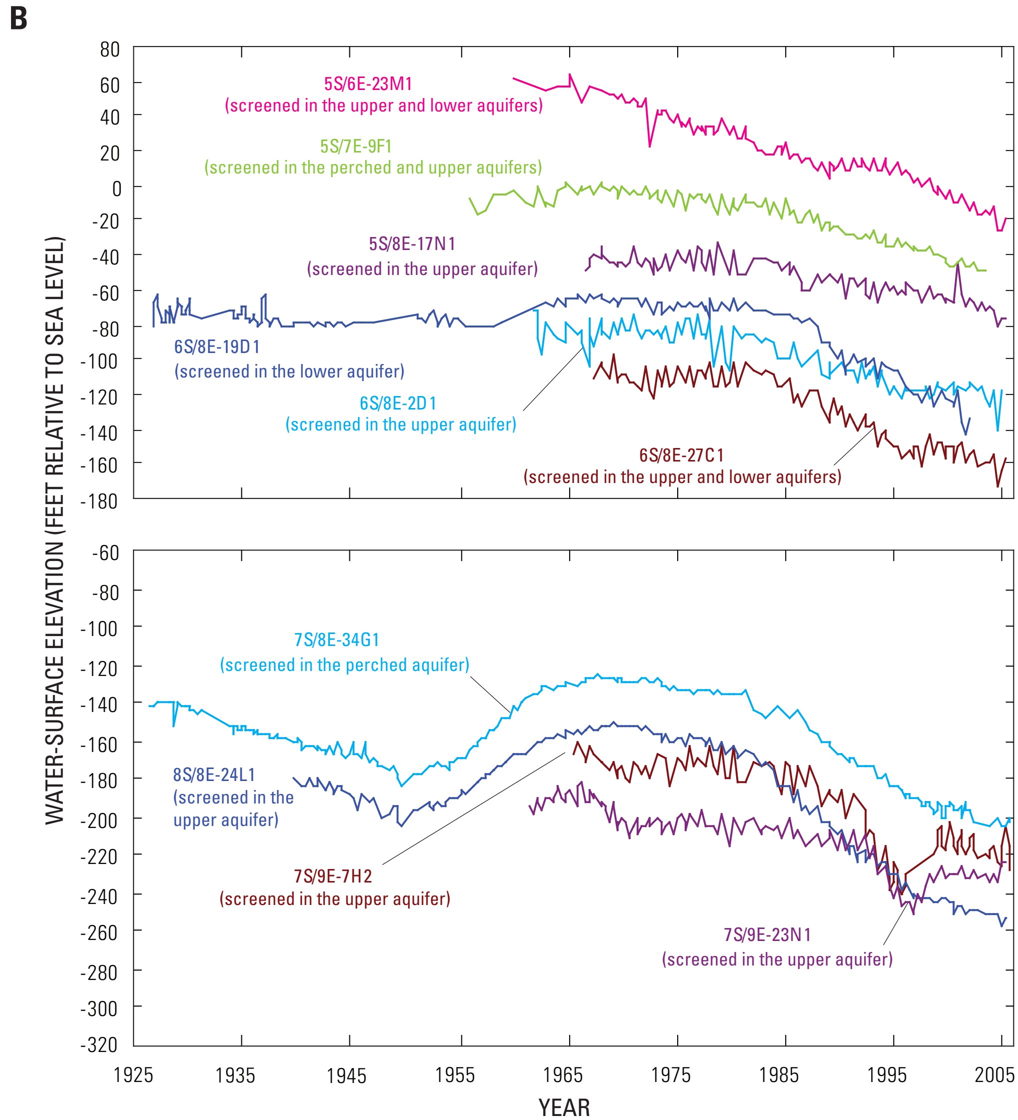

Figure 4. Continued.

Comparisons of GPS measurements made at 20 geodetic monuments in 2000 and in 2005 indicate that the land-surface elevation changed –312 to +25 mm ±42 mm (–1.0 to +0.08 ft ±0.14 ft) during the 5-year period (table 1). Changes at 14 of the 20 monuments (DEEP, MANI, MAGF, OSDO, DUNE, COCH, R70R, 5211, JA54, CAHU, C132, K572, K70, and C427) exceeded the maximum uncertainty of ±42 mm (±0.14 ft) at the 95-percent confidence level, indicating that subsidence occurred at these monuments between August 2000 and August 2005. Changes at 6 of the 20 monuments (S753, PAIN, JOHN, C101, P572, and G70) did not exceed the maximum uncertainty of ±42 mm (±0.14 ft) at the 95-percent confidence level indicating that the vertical positions of these monuments were similar in August 2000 and in August 2005.

GPS measurements were made at 16 geodetic monuments (DUNE, COCH, R70R, 5211, CAHU, S753, C132, PAIN, C101, K572, JOHN, P572, SWC, K70, C427, and G70) during at least 3 of the 4 surveys, thus permitting calculations and comparisons of subsidence rates. A seventeenth monument, 54JA, was surveyed in 1996 and 1998 and was then replaced with monument JA54 (about 6 m [20 ft] northwest from 54JA) for the 2000 and 2005 surveys; although the monument location was changed slightly, rates of subsidence were compared. Because GPS data indicated the heights of PAIN, JOHN, and G70 were fairly stable (fig. 4A), the subsidence rates of the other 14 monuments are discussed. Eight of the fourteen monuments (DUNE, R70R, 54JA/JA54, CAHU, C132, K572, K70, and C427) show increased subsidence rates between 2000 and 2005 compared with subsidence rates before 2000; the most marked subsidence-rate increases occurred at monuments DUNE, 54JA/JA54, C132, and K70, where rates increased by a factor of about 2 or 3, and at monument K572, where rates increased by a factor of about 10 (fig. 4A). Subsidence rates at monuments COCH, 5211, and SWC were fairly steady since 1996, whereas measurements at geodetic monuments S753 and P572 indicated fairly steady subsidence rates for 1996-2000 followed by insignificant subsidence for 2000–2005. Subsidence rates continuously decreased at monument C101 (fig. 4A).

Ground-Water Levels

In the northern and central parts of the geodetic network (near DUNE, COCH, MAGF, MANI, OSDO, R70R, DEEP, 5211, JA54, CAHU, S753, and C132), where significant subsidence was measured by 2005, water levels generally showed seasonal fluctuations superimposed on longer-term water-level declines during 1995–2005 (fig. 4A). It should be noted that wells 5S/8E-17N1 and 5S/8E-20C2 on the west side of the San Andreas fault are shown on figure 4A together with the geodetic monument COCH, which is on the east side of the fault (fig. 3); thus, hydrologic conditions in these wells probably do not represent hydrologic conditions at COCH.

In the southwestern part of the network near monuments C101 and P572, where small or insignificant amounts of subsidence were measured, and near monument C427, where significant amounts of subsidence were measured, water levels showed seasonal fluctuations superimposed on longer-term water-level declines during 1995-2005 (fig. 4A).

In the southeastern part of the network near K572, JOHN, K70, G70, and PAIN, where some monuments subsided significantly and others changed insignificantly, water levels generally showed seasonal variability superimposed on fairly stable or rising water levels during 1995 and 2005 (fig. 4A).

The relationship between ground-water-level changes and concurrent vertical changes at the geodetic monuments is not clearly defined. Complications that contribute to the difficulty in deciphering the relationship include the low frequency of both GPS and water-level measurements, and the complex, often significantly delayed mechanical responses of the aquifer-system to ground-water-level changes. However, most of the monuments subsided significantly between 1996 and 2005— many at significantly increased rates between 2000 and 2005—and water levels generally declined significantly during this period and during most of the last century (fig. 4). The coincident areas of subsidence and declining water levels suggest that aquifer-system compaction may be causing subsidence. If water levels have declined sufficiently to exceed the preconsolidation stress, the subsidence may be permanent. Although this longer term relationship seems more straightforward, the complication of tectonically-induced subsidence also is introduced because it also occurs on longer time scales. However, the CGPS stations used as constraints for each of the GPS datasets were fairly stable between 1996 and 2005, indicating that tectonic-induced vertical crustal motion did not significantly contribute to the subsidence measured at the geodetic monuments in the network.

InSAR Methodology

Using Interferometric Synthetic Aperture Radar (InSAR) is an effective way to measure vertical changes of land surface. InSAR is a satellite-based remote sensing technique that can detect centimeter-level ground-surface deformation over a 100 km^2 area with a spatial resolution of 90 m or less. Synthetic Aperture Radar (SAR) imagery is produced by reflecting radar signals off a target area and measuring the two-way travel time between the target area and the satellite. InSAR uses two SAR scenes of the same area taken at different times and “interferes” (differences) them, resulting in maps called interferograms that show line-of-sight ground-surface displacement (range change) between the two time periods. The generation of an interferogram produces two components, amplitude and phase. The amplitude is the measure of the radar signal intensity returned to the satellite and shows roads, mountains, and other reflective features (similar to the image shown in fig. 5); the phase component is proportional to range change and shows the coherent displacements imaged by the radar (figs. 6A, 7A, 8A). If the ground has moved away from (subsidence) or towards (uplift) the satellite between the times of the two acquisitions (the “timeline”), a slightly different portion of the wavelength is reflected back to the satellite resulting in a measurable phase shift that is proportional to range change. The map of phase shifts, or interferogram, is depicted with a repeating color scale that shows relative range change between the first and the second acquisitions. In this report, one complete color cycle (fringe) represents 28.3 mm (0.09 ft) of range change. Assuming all the motion is vertical, the indicated range change is about 90- to 95-percent of true vertical ground motion, depending on the satellite look angle and the location of the target area. The direction of change—subsidence or uplift—is indicated by the color progression of the fringe(s) from the outer edge of a deforming feature toward its center. For interferograms in this report, the color-fringe progression of yellow-green-blue-pink indicates subsidence; the opposite progression indicates uplift.

InSAR signal quality depends partly on satellite position, atmospheric effects, ground cover, land-use practices, and timeline of the interferogram. Strict orbital control is required to precisely control the look angle and position of the satellite. Successful application of the InSAR technique is contingent on looking at the same point on the ground from the same position in space so that the horizontal distance between each satellite pass, or perpendicular baseline, is minimized. Perpendicular baselines generally greater than about 200 m (656 ft) usually produce excessive topographic effects (parallax) that can mask the deformation signal. Phase shifts can be caused by varying atmospheric mass that is associated with different elevations. A digital elevation model (DEM) is used in the interferogram generation process to reduce the atmospheric effects caused by elevation differences (and also to georeference the image). Phase shifts also can be caused by laterally variable atmospheric conditions such as clouds or fog, as the non-uniform distribution of water vapor differentially slows the radar signal over an image. Atmospheric artifacts can be identified by using several independent interferograms, which are defined as interferograms that do not share a common SAR image. When apparent ground motion is detected in only one interferogram, or a set of interferograms sharing a common SAR image, then the apparent motion likely is due to atmospheric phase delay or other error source and can be discounted.

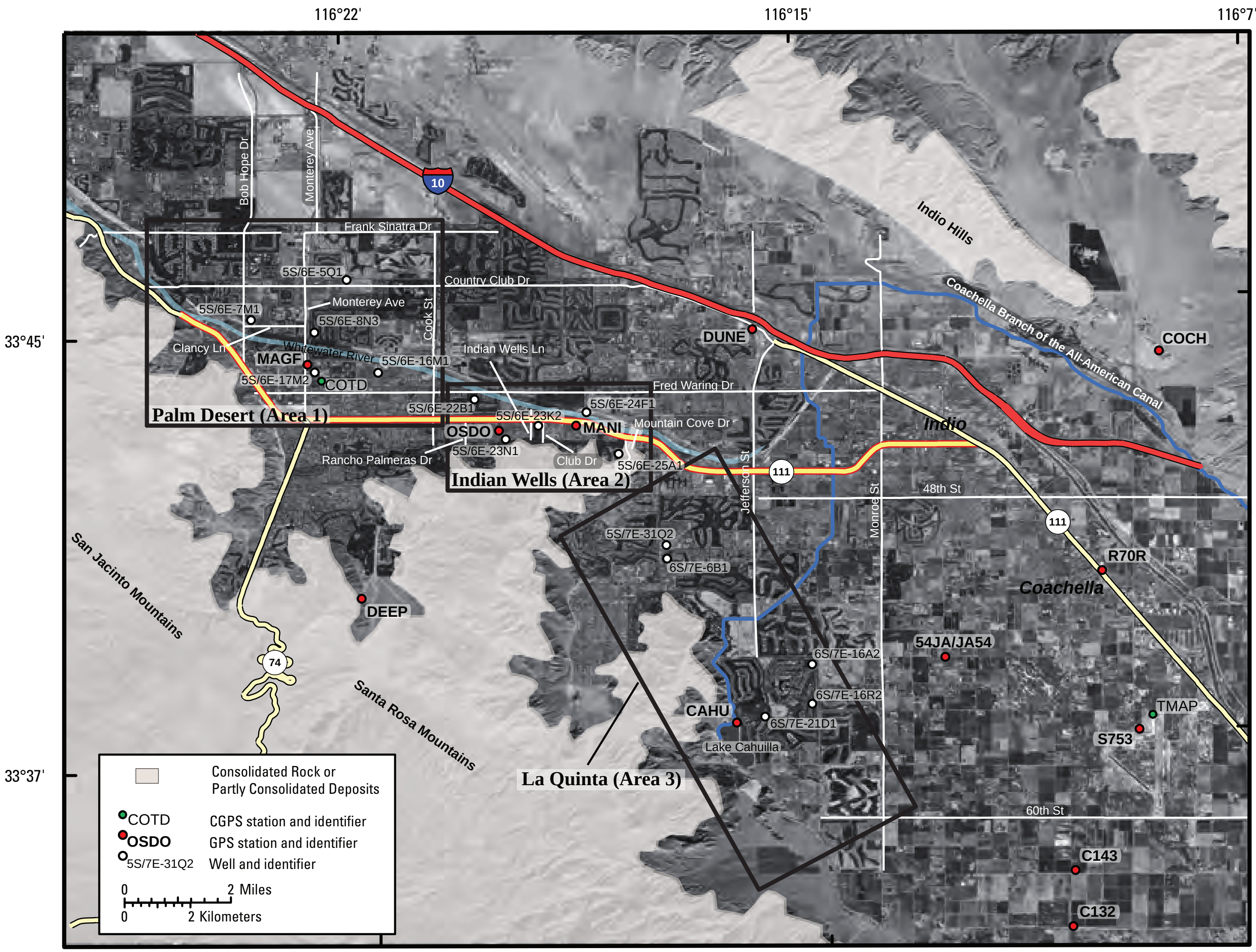

Figure 5. Image showing land-surface features, consolidated rock, Global Positioning System (GPS) stations, two Continuous Global Positioning System (CGPS) stations, three areas of subsidence, and selected roads and production wells, Coachella Valley, California. (Hydrographs for production wells are shown in figure 9.)

A

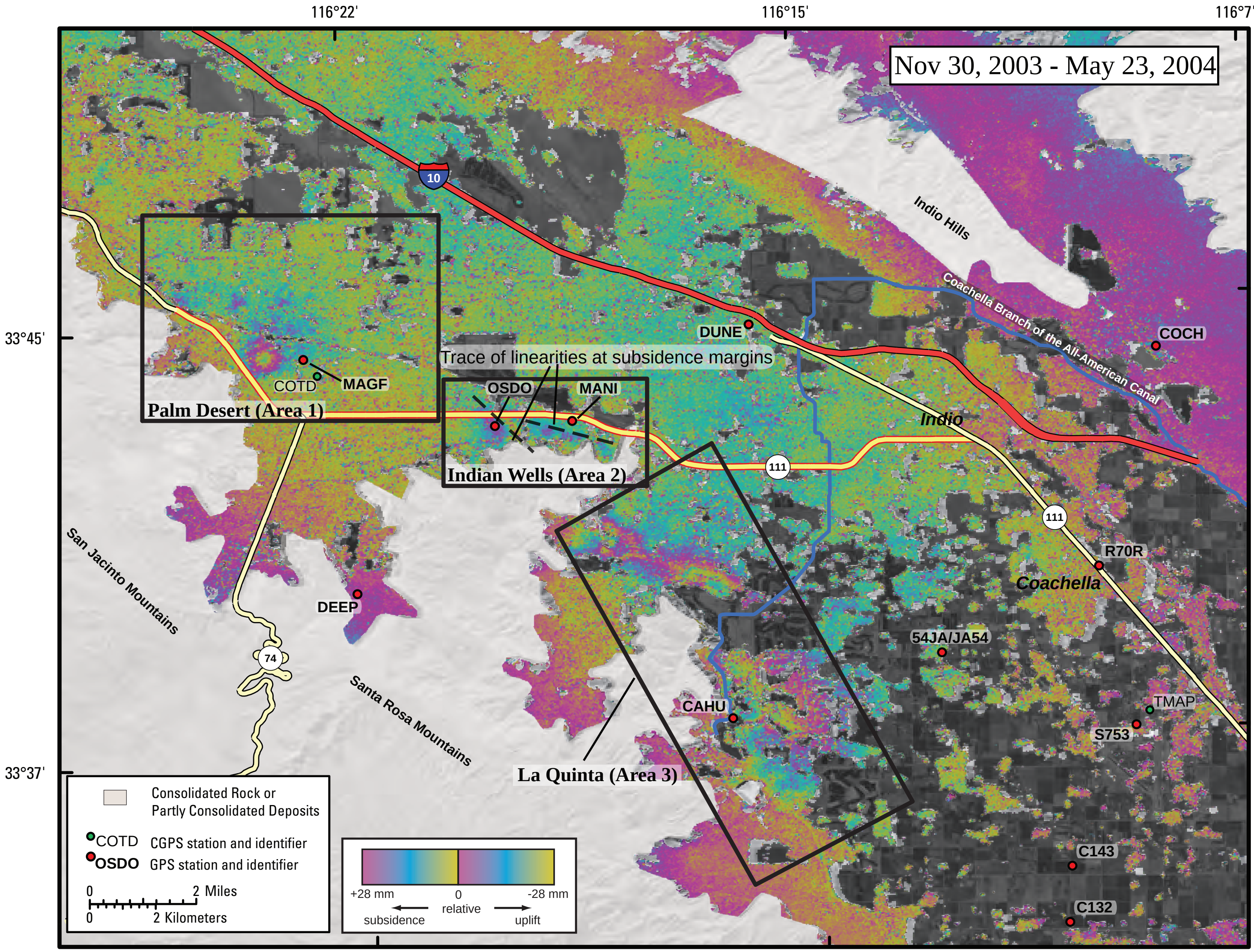

Figure 6. Areas of subsidence, linearities at subsidence margins, consolidated rock, GPS stations, and two CGPS stations in the Coachella Valley, California, for November 30, 2003, through May 23, 2004, (A) as shown on the interferogram, and (B) as shown by subsidence contours interpreted from the interferogram in A.

B

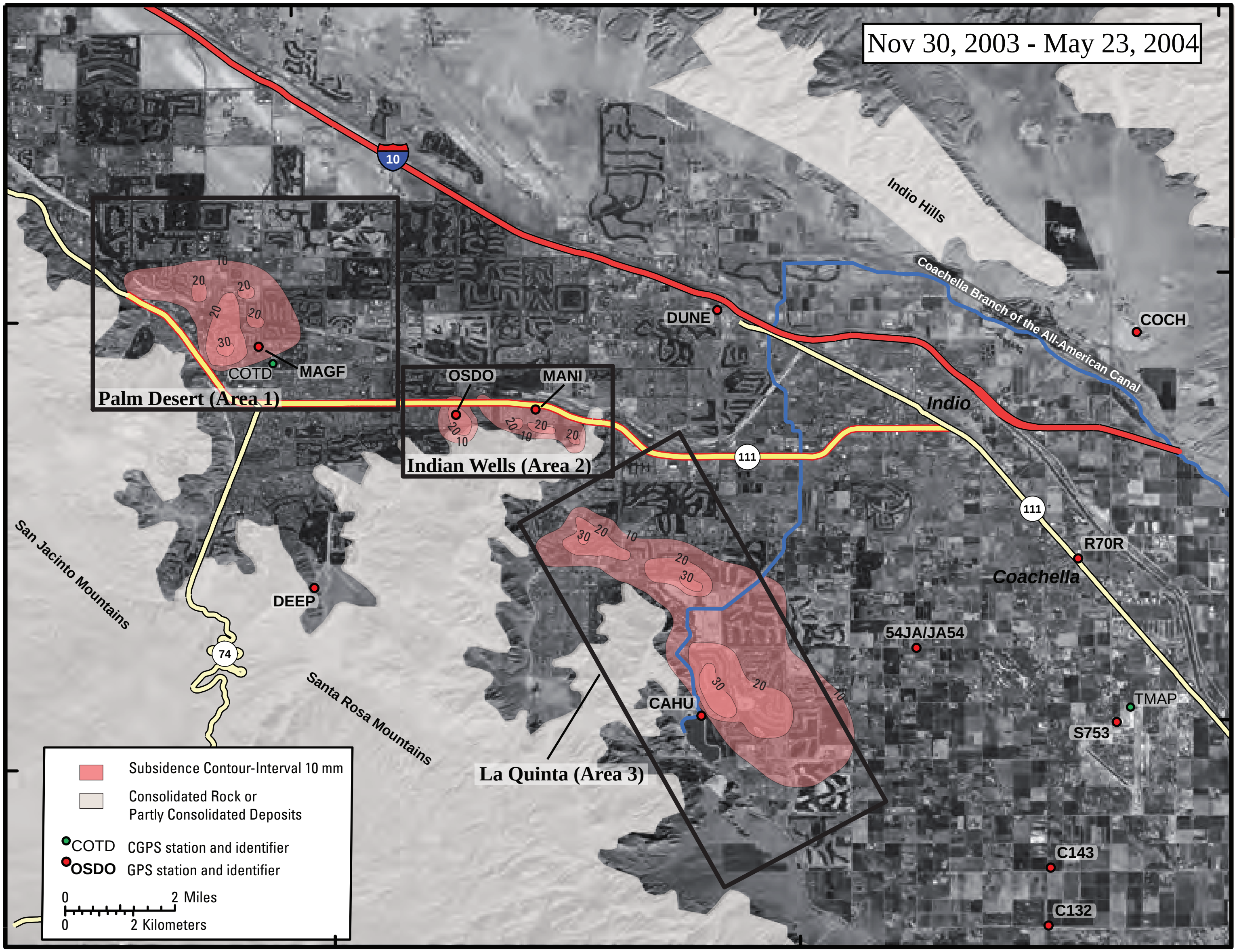

Figure 6. Continued.

A

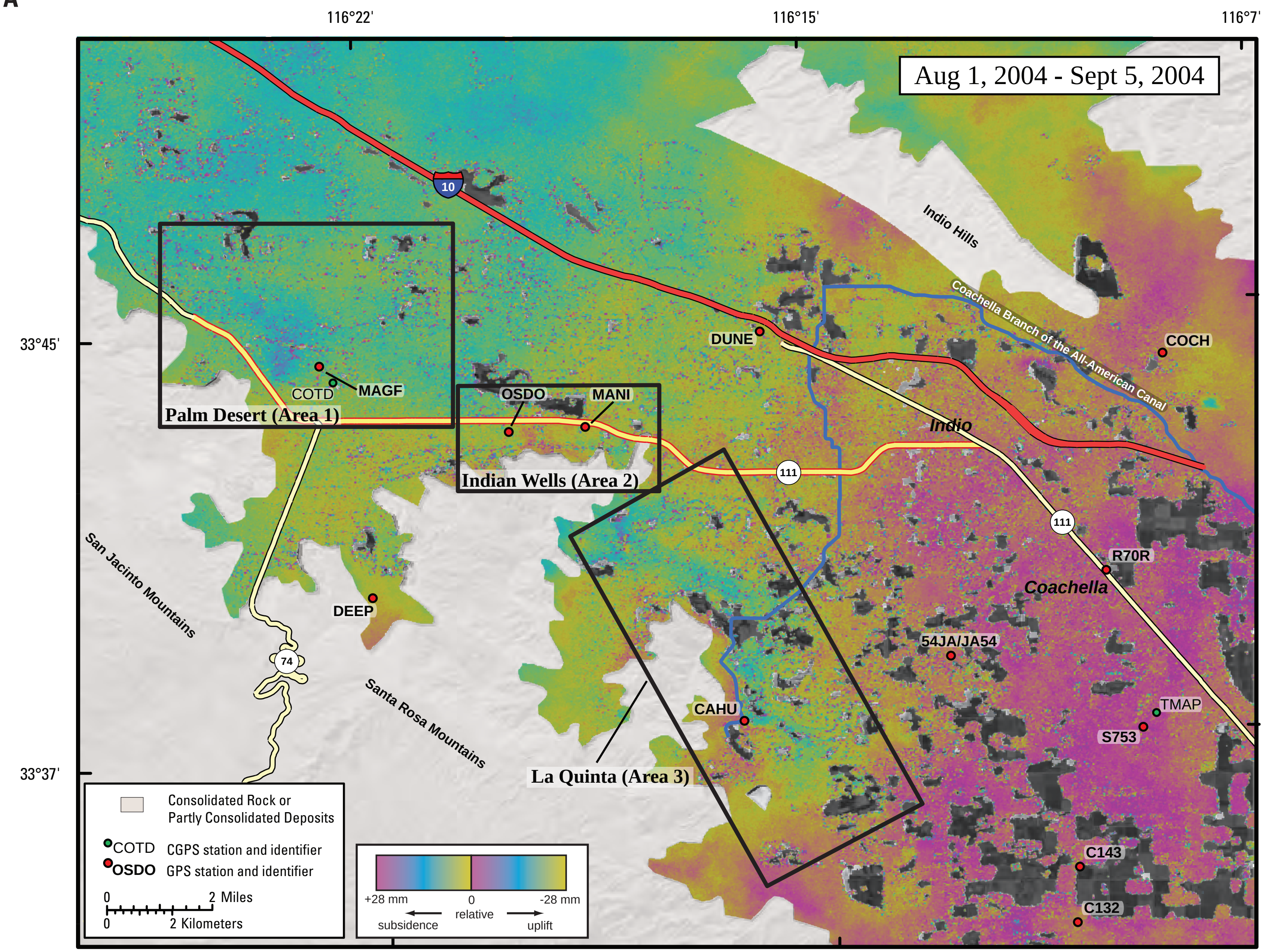

Figure 7. Areas of subsidence, consolidated rock, GPS stations, and two CGPS stations in the Coachella Valley, California, for August 1, 2004, through September 5, 2004, (A) as shown on the interferogram, and (B) as shown by subsidence contours interpreted from the interferogram in A.

B

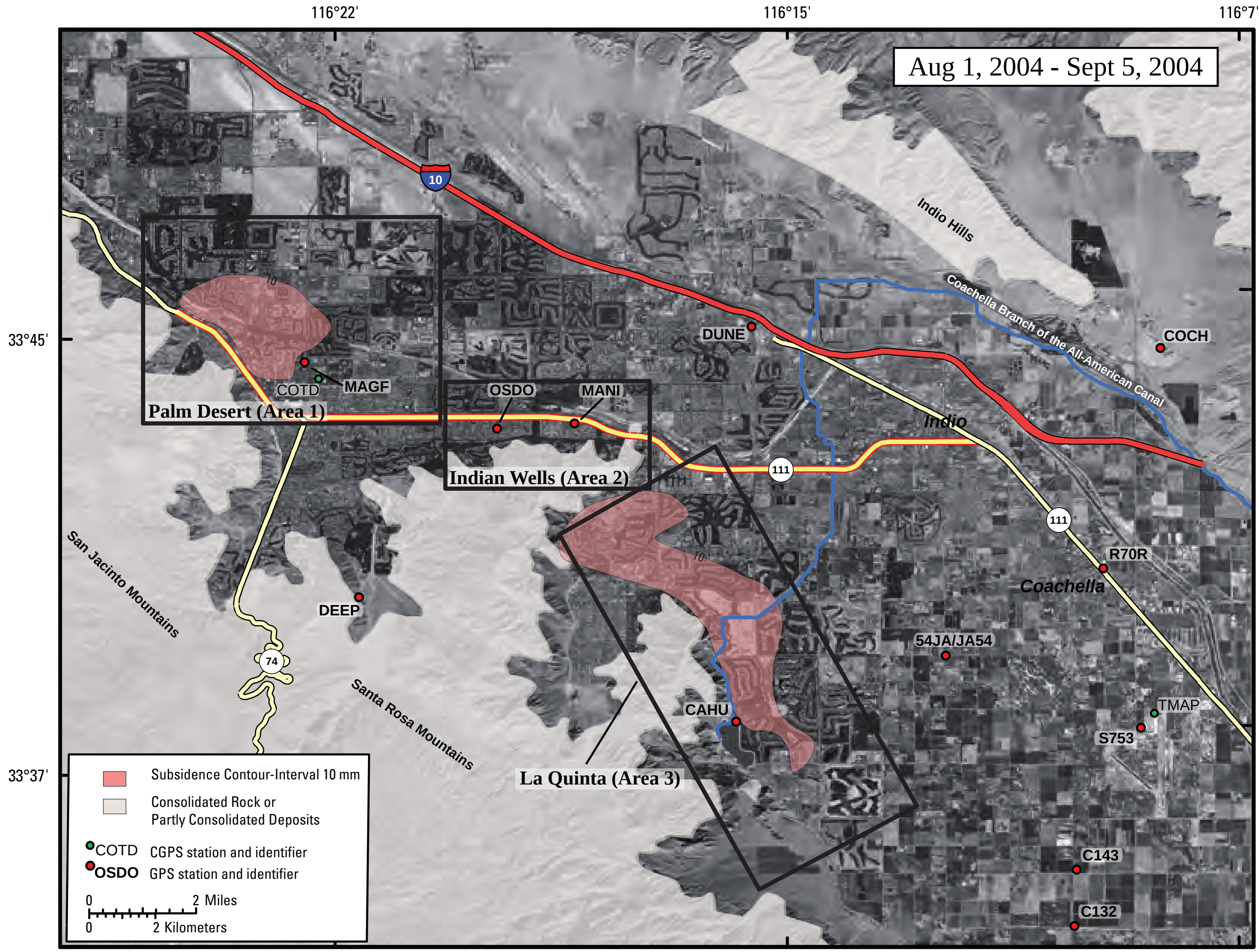

Figure 7. Continued.

A

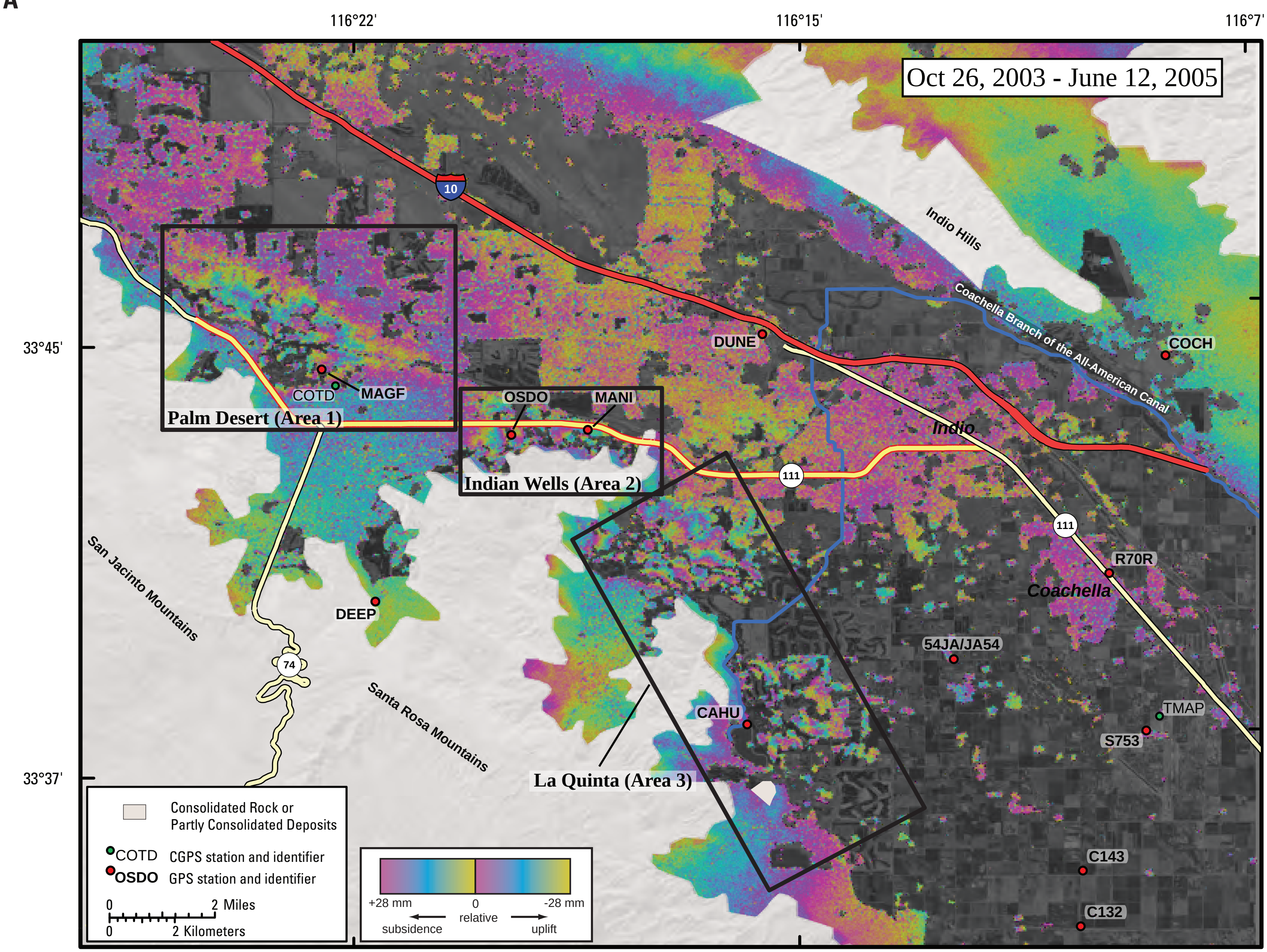

Figure 8. Areas of subsidence, consolidated rock, GPS stations, and two CGPS stations in the Coachella Valley, California, for October 26, 2003, through June 12, 2005, (A) as shown on the interferogram, and (B) as shown by subsidence contours interpreted from the interferogram in A.

B

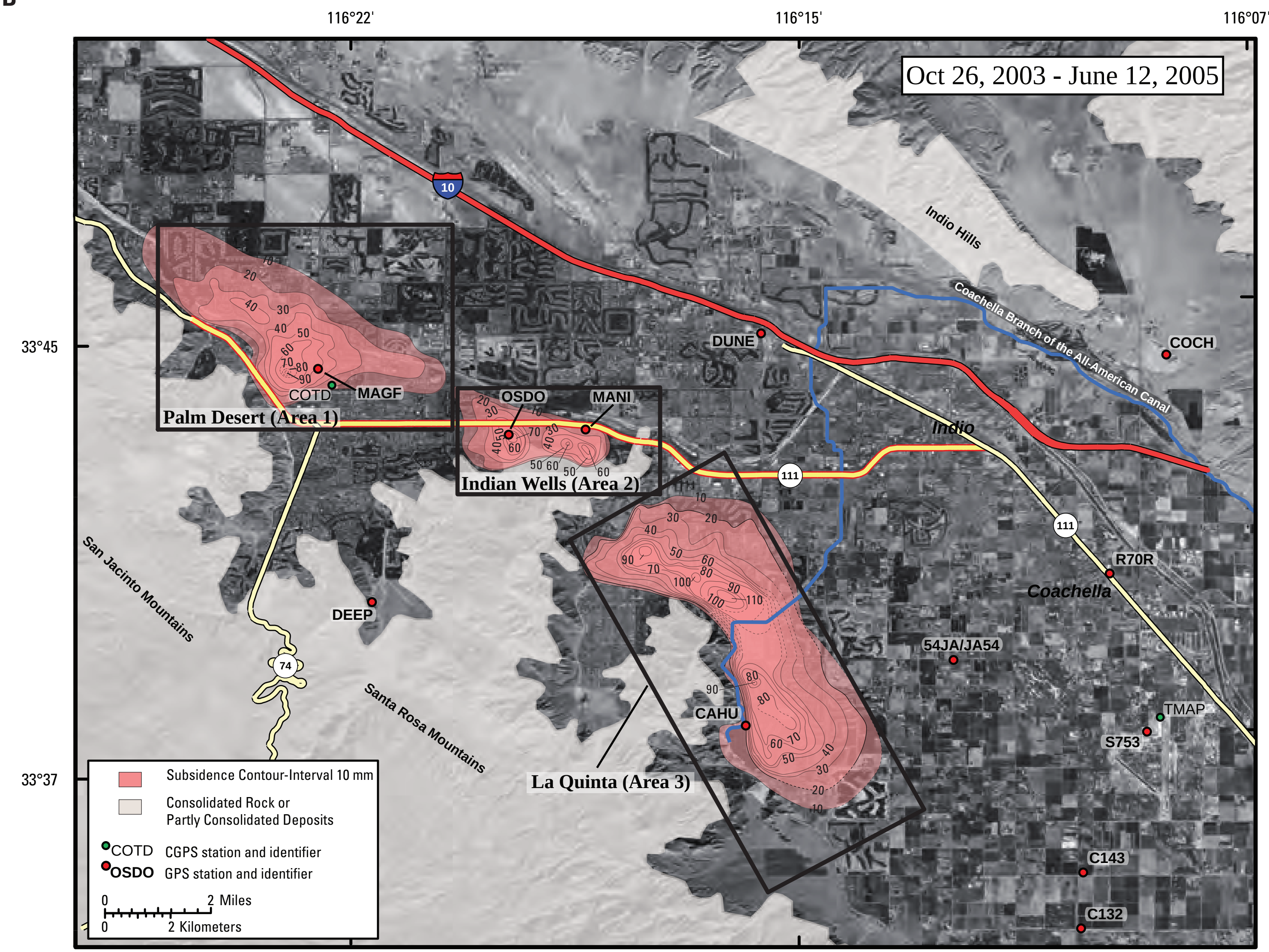

Figure 8. Continued.

The type and density of ground cover also can significantly affect interferogram quality. Densely forested areas are prone to reflect poor signals because the C-band wavelength (56.6 mm or 0.18 ft) cannot effectively penetrate thick vegetation and is either absorbed or reflected back to the satellite from varying depths within the canopy resulting in incoherent signal (shown as randomized colors on an interferogram). Sparsely vegetated areas and urban centers, however, generally reflect coherent signals because bare ground, roads, and buildings have high reflectivities and are relatively uniform during at least some range of InSAR timelines. Certain land-use practices, such as farming, which is prevalent in the Coachella Valley, also cause incoherent signal return. The tilling and plowing of farm fields causes large and nonuniform ground-surface change that cannot be resolved with InSAR. In both urban and non-urban areas, signal quality also is adversely affected by longer timelines, as there is more opportunity for nonuniform change and temporal decorrelation of the radar signal. Because Coachella Valley is fairly flat and contains several urban centers, the area lends itself to confident InSAR interpretations because most of the error sources are minimized. The agricultural fields in the area, however, cause significant InSAR signal incoherence that cannot be reliably interpreted using the coherent InSAR techniques described here.

Data from the European Space Agency's (ESA) ENVISAT satellite were obtained for analysis. The multi-mission ENVISAT platform was launched in 2002 and is currently (2007) the only ESA-owned fully functional SAR satellite. (The previous studies [Sneed and others 2001, 2002] used ESA's ERS-1 and -2 satellites; ERS-1 was turned off in 1999 and ERS-2 is no longer routinely suitable for interferometry). The satellite is side-looking and orbits the Earth at an altitude of approximately 800 km (500 mi), and has a 35-day repeat orbit. Twenty SAR images, acquired between February 26, 2003 and September 25, 2005, were used to produce 22 interferograms having timelines that range from 35 to 595 days. The three interferograms shown in this report were selected on the basis of overall interferogram quality and timeline length. Figures 6, 7, and 8 show interferograms representing timelines ranging from 35 days to 595 days; the variable timelines demonstrate temporal decorrelation of an interferogram (coherency) and on subsidence feature characteristics, such as geographic extent.

InSAR Results

The interferograms of the Coachella Valley show significant land-surface-elevation changes in at least four areas. Land subsidence occurred in three of the areas—Palm Desert (Area 1), Indian Wells (Area 2), and La Quinta (Area 3) (figs. 6, 7, 8; table 2)—and both subsidence and uplift apparently occurred in one of the areas—Indio-Coachella—between February 26, 2003, and September 25, 2005. The interferograms show that other local areas in the Coachella Valley also may have deformed (figs. 6, 7, 8), but the extent of these areas and the amount of deformation generally are small compared with the three areas of land subsidence discussed in this section.

Table 2. Vertical change measured using interferometric synthetic aperture radar (InSAR) for 3 areas in the Coachella Valley, California, 2003–2005.

[Negative values for magnitude indicate subsidence. **Bold** type indicates conservative value owing to increased incoherency associated with longer timelines. Shading: Green shade indicates that the interferogram is shown in figure 6A; brown shade indicates that the interferogram is shown in figure 7A; and pink shade indicates that the interferogram is shown in figure 8A. ft, foot; i, incoherent; mm, millimeter]

Acquisition dates	Palm Desert (Area 1)			Indian Wells (Area 2)				La Quinta (Area 3)					
				West bowl		East bowl		North		Central		South	
start date-end date	time-line (days)	magnitude (mm)	magnitude (ft)	magnitude (mm)	magnitude (ft)	magnitude (mm)	magnitude (ft)	magnitude (mm)	magnitude (ft)	magnitude (mm)	magnitude (ft)	magnitude (mm)	magnitude (ft)
2/26/2003–6/11/2003	105	–20	–0.07	–5	–0.02	0	0	i	i	i	i	i	i
5/7/2003–9/8/2004	490	**–90**	**–0.30**	–60	–0.20	–50	–0.16	–90	–0.30	**–120**	**–0.39**	–60	–0.20
9/24/2003–8/4/2004	315	–80	–0.26	–30	–0.10	–30	–0.10	–50	–0.16	–60	–0.20	–60	–0.20
10/26/2003–6/27/2004	245	–45	–0.15	–25	–0.08	–25	–0.08	–30	–0.10	–45	–0.15	i	i
10/26/2003–11/14/2004	385	**–70**	**–0.23**	–40	–0.13	–35	–0.11	–40	–0.13	**–80**	**–0.26**	–50	–0.16
10/26/2003–2/27/2005	490	**–60**	**–0.20**	**–40**	**–0.13**	–40	–0.13	**–60**	**–0.20**	**–70**	**–0.23**	**–60**	**–0.20**
10/26/2003–6/12/2005	595	**–90**	**–0.30**	**–70**	**–0.23**	–60	–0.20	–90	–0.30	–110	–0.36	–90	–0.30
11/30/2003–5/23/2004	175	–35	–0.11	–20	–0.07	–20	–0.07	–30	–0.10	–30	–0.10	–30	–0.10
11/30/2003–7/17/2005	595	**–90**	**–0.30**	–40	–0.13	–40	–0.13	–70	–0.23	100	0.33	–60	–0.20
5/23/2004–1/23/2005	245	–60	–0.20	–30	–0.10	–25	–0.08	–70	–0.23	–50	–0.16	–60	–0.20
5/23/2004–7/17/2005	420	–90	–0.30	–50	–0.16	–40	–0.13	–70	–0.23	–90	–0.30	–60	–0.20
6/27/2004–11/14/2004	140	–40	–0.13	–20	–0.07	–15	–0.05	–40	–0.13	–40	–0.13	–50	–0.16
8/1/2004–9/5/2004	35	–15	–0.05	0	0	0	0	–15	–0.05	–10	–0.03	–10	–0.03
8/1/2004–4/3/2005	245	–50	–0.16	–30	–0.10	–20	–0.07	–40	–0.13	–40	–0.13	–50	–0.16
9/5/2004–4/3/2005	210	–50	–0.16	–25	–0.08	–15	–0.05	–40	–0.13	–30	–0.10	–30	–0.10
11/14/2004–12/19/2004	35	–10	–0.03	0	0	0	0	–5	–0.02	0	0	5	0.02
11/14/2004–2/27/2005	105	–25	–0.08	–15	–0.05	–10	–0.03	–20	–0.07	0	0	10	0.03
12/19/2004–2/27/2005	70	–15	–0.05	–10	–0.03	–5	–0.02	–15	–0.05	–10	–0.03	–10	–0.03
1/23/2005–7/17/2005	175	–30	–0.10	–20	–0.07	–10	–0.03	–30	–0.10	–40	–0.13	–30	–0.10
2/27/2005–6/12/2005	105	–20	–0.07	–15	–0.05	–5	–0.02	–10	–0.03	–20	–0.07	–25	–0.08
5/8/2005–9/25/2005	140	–40	–0.13	–20	–0.07	–10	–0.03	–30	–0.10	–25	–0.08	–30	–0.10
7/17/2005–9/25/2005	70	–15	–0.05	–15	–0.05	–5	–0.02	–20	–0.07	–15	–0.05	–15	–0.05

Land Subsidence in the Palm Desert Area (Area 1)

A subsidence signal was detected in Palm Desert (Area 1 in figs. 5, 6, 7, 8); this signal was previously detected by Sneed and others (2001, 2002) using InSAR methods. All 22 interferograms analyzed for this study show subsidence in this area (for example, figs 6, 7, 8; table 2). The part of the signal that has the largest magnitude is nearly circular (slightly elongated north to south); in longer-term interferograms, it is as large as about 2 km (1.2 mi) in diameter and has an area of about 4 km^2 (1.5 mi^2) (fig. 8). This part of the signal is approximately bounded by Clancy Lane on the north, Fred Waring Drive on the south, Highway 111 and Bob Hope on the west, and Monterey Avenue on the east (fig. 5). The part of the signal that is smaller in magnitude extends to the north and east, has a pronounced northwest–southeast elongation, and has a much larger extent. The extent of this part of the signal is larger in interferograms representing longer timelines (fig. 8) than interferograms representing shorter timelines (fig. 7), but generally extends to the northwest where Frank Sinatra Drive intersects the Whitewater River channel, to the north beyond Country Club Drive, and to the east as far as Cook Street (fig. 5). The San Jacinto and Santa Rosa Mountains, which are outcropping consolidated rock, may act as barriers to subsidence farther to the south and southwest; and the Indio Hills, which are outcropping partly consolidated deposits, may act as barriers to subsidence farther to the northeast (figs. 2, 5). A lack of barriers to the northwest and southeast may explain the pronounced elongation of the subsidence signal in these directions. Several deformation timeseries can be constructed from InSAR data. The longest timeseries timeline (840 days)—May 7, 2003 to September 25, 2005—was constructed using 3 interferograms (5/7/2003-9/8/2004; 9/5/2004-4/3/2005; 5/8/2005-9/25/2005) and indicates that about 180 mm (0.59 ft) of subsidence occurred in the Palm Desert area during this time—a rate of more than 6 mm/month (0.02 ft/month) (Area 1 in figs. 5, 6, 7, 8, 9A). Sneed (2001; 2002) reported that about 150 mm (0.49 ft) of subsidence occurred in this area during 1,541 days between 1996 and 2000, which is equivalent to a rate of about 3 mm/month (0.1 ft/month). These data indicate that subsidence rates have doubled since 2000.

Land Subsidence in the Indian Wells Area (Area 2)

In the Indian Wells area, two distinct subsidence signals were detected, termed the western bowl and the eastern bowl (Area 2 in figs. 5, 6, 7, 8). Sneed and others (2002) discussed a possible additional subsidence signal as suspect about 1 km (0.6 mi) southeast of the eastern subsidence bowl because of the proximity of this area to steep topographic terrain. The shorter timelines and multiple interferograms analyzed during this current study show that it is an extension of the eastern subsidence bowl (for example, fig. 6). Twenty of the 22 interferograms analyzed for this study show the western bowl and 19 show the eastern bowl (for example, figs 6, 8; table 2). The two interferograms with the shortest timelines (35 days) do not show either the western or eastern subsidence bowl (for example, fig. 7) and one interferogram of relatively low quality (not shown) with a 105-day timeline does not show the eastern bowl (table 2). The western subsidence bowl is approximately bounded by Fred Waring Drive on the north, the Santa Rosa Mountains on the south, Rancho Palmeras Drive on the west, and Indian Wells Lane on the east (fig. 5). The eastern subsidence bowl is approximately bounded by Highway 111 on the north, the Santa Rosa Mountains on the south, Club Drive on the west, and Mountain Cove Drive on the east (fig. 5). Distinct northwest-southeast linearities shown near the northern margins of the pair of subsiding bowls suggest the presence of barriers to ground-water flow or abrupt changes in lithology that control the northern extent of subsidence (fig. 6). The western bowl, which is elongated northwest–southeast, is as large as about 2.3 km (1.4 mi) long and about 1.8 km (1.1 mi) wide (northeast–southwest) and has an area of about 4.1 km^2 (1.6 mi^2) in longer-term interferograms. The eastern bowl, which also is elongated northwest–southeast, is as large as about 2.3 km (1.4 mi) long and ranges from about 0.3 to 0.8 km (0.2 to 0.5 mi) wide (northeast–southwest) and has an area of 1.2 km^2 (0.5 mi^2) (Area 2 in figures 6 and 8). The maximum subsidence for the western bowl was about 105 mm (0.34 ft) and for the eastern bowl was about 75 mm (0.25 ft) from May 7, 2003 to September 25, 2005 (fig. 9A); the equivalent rates are nearly 4 mm/month (0.013 ft/month) and nearly 3 mm/month (0.01 ft/month) for the western and eastern bowls, respectively. Sneed (2001; 2002) reported that about 80 mm (0.26 ft) of subsidence occurred in each bowl between 1996 and 2000; the equivalent rate is about 1.6 mm/month (0.005 ft/month). These data indicate that subsidence rates have doubled since 2000.

Land Subsidence in the La Quinta Area (Area 3)

A third area of subsidence was detected in the La Quinta area (Area 3 in figs. 5, 6, 7, 8). All 22 interferograms analyzed for this study show subsidence in this area (for example, figs. 6, 7, 8; table 2). Sneed and others (2002) analyzed 2 interferograms with timelines of 315 and 350 days and suggested Area 3 consisted of two separate areas of subsidence—termed the La Quinta and the Lake Cahuilla areas of subsidence—because the interferograms were not coherent throughout the area. Similarly for the interferograms analyzed for this current study, the longer-term interferograms were incoherent near the central part of the subsiding area (for example, figs. 6 and 8); however, the shorter-term interferograms show that this subsidence area likely is continuous, and is termed the La Quinta subsidence area for this report (for example, fig. 7A). The La Quinta subsidence area is about 10 km (6 mi) in length (northwest-southeast) and is as much as 3 km (1.9 mi) in width. The area is approximately bounded by 48th Street (if extended westward) on the north, 60th Street (if extended westward) on the south, the Santa Rosa Mountains on the west, and streets varying from Jefferson Street to Monroe Street on the east (because the subsidence area trends northwest-southeast) (fig. 5). Different portions of this elongate subsidence bowl are subsiding at different rates; for May 7, 2003 to September 25, 2005, subsidence was 160 mm (0.52 ft) in the northern part, 175 mm (0.57 ft) in the central part, and 120 mm (0.39 ft) in the southern part (fig. 9A); equivalent subsidence rates are about 6 mm/month (0.02 ft/month) for the northern and central parts and more than 4 mm/month (0.013 ft/month) for the southern part. Sneed (2002) reported that about 80 mm (0.26 ft) of subsidence occurred in the northern part between 1998 and 2000 and is equivalent to a subsidence rate of more than 3 mm/month (0.01 ft/month). Sneed (2001; 2002) reported that about 35 mm (0.11 ft) of subsidence occurred in the southern part between 1996 and 2000 and is equivalent to a subsidence rate of nearly 1 mm/month (0.003 ft/month). These data indicate that subsidence rates have doubled in the northern part and increased by about a factor of 4 in the southern part since 2000.

Deformation in the Indio-Coachella Area

Indio-Coachella has not been previously discussed as an area of deformation. The shorter timelines of InSAR data presented in this report as opposed to those presented in Sneed and others, 2001 and Sneed and others 2002, show land-surface-elevation changes in the Indio-Coachella area which appear to mostly be uplift or stable; however, the apparent deformation is suspect. As was mentioned in the InSAR Methodology section, interferograms show relative deformation, not absolute deformation. Because much of the basin is subsiding as is shown by the GPS results, it is likely that the Indio-Coachella area only appears to be uplifting as proximal areas in the basin are subsiding around it. The Indio-Coachella area could actually be subsiding at slower rates than proximal areas of the basin, which would appear as relative uplift in an interferogram. Because the deformation interpretations are suspect, this area is not discussed further in this report.

Ground-Water Levels

All the areas where significant subsidence was detected using InSAR—Palm Desert, Indian Wells, and La Quinta—coincide with or are near areas where ground-water pumping generally caused ground-water levels to decline. Available water-level data indicate that water levels measured in 2005 in many wells in the Palm Desert, Indian Wells, and La Quinta areas were at the lowest levels in their recorded histories (fig. 9B). The coincident areas of the subsidence signals and the declining water levels, and the localized character of the subsidence signals typical of subsidence caused by localized pumping, strongly suggest a relation between subsidence and ground-water-level declines. The stresses imposed by the declining water levels and the significant subsidence at the three areas revealed by InSAR indicate that the water levels may have exceeded the preconsolidation stress, and if so, the subsidence may be permanent.

While ground-water-level data are too sparse to evaluate the short-term effect on vertical land-surface changes shown by the InSAR results, the available ground-water-level and InSAR data can be used to draw some inferences about the affected aquifer system. In Palm Desert (Area 1 in figs. 6, 7, 8), the area of maximum subsidence is concentric. Although water-level data are measured infrequently and are not available within the area of the concentric InSAR signal, data for the surrounding region indicate that water-level declines have been fairly uniform. The concentric subsidence shape suggests that the stress primarily causing the subsidence is near the center of the concentric shape and that sediments constituting the aquifer system in the area are fairly homogenous as the sediments responded uniformly to similar water-level declines in areas surrounding the center of the subsidence bowl.

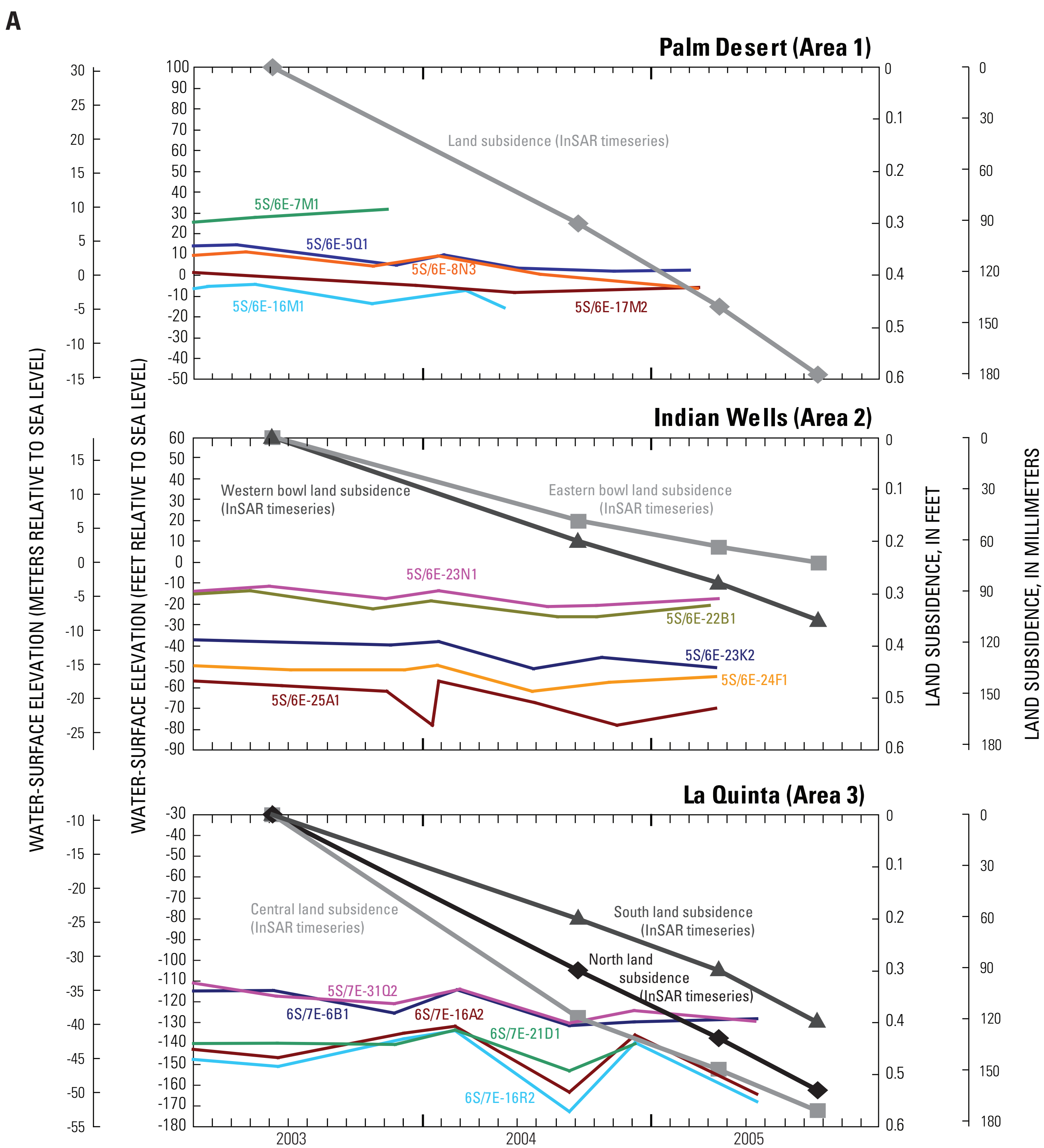

Figure 9. Hydrographs showing (A) water-surface elevations for selected production wells, and InSAR timeseries showing land subsidence for 5/7/2003–9/25/2005, and (B) water-surface elevations for the same production wells for 1970–2005 in the three InSAR-detected land subsidence areas in the Coachella Valley, California.
(See figure 5 for well locations.)

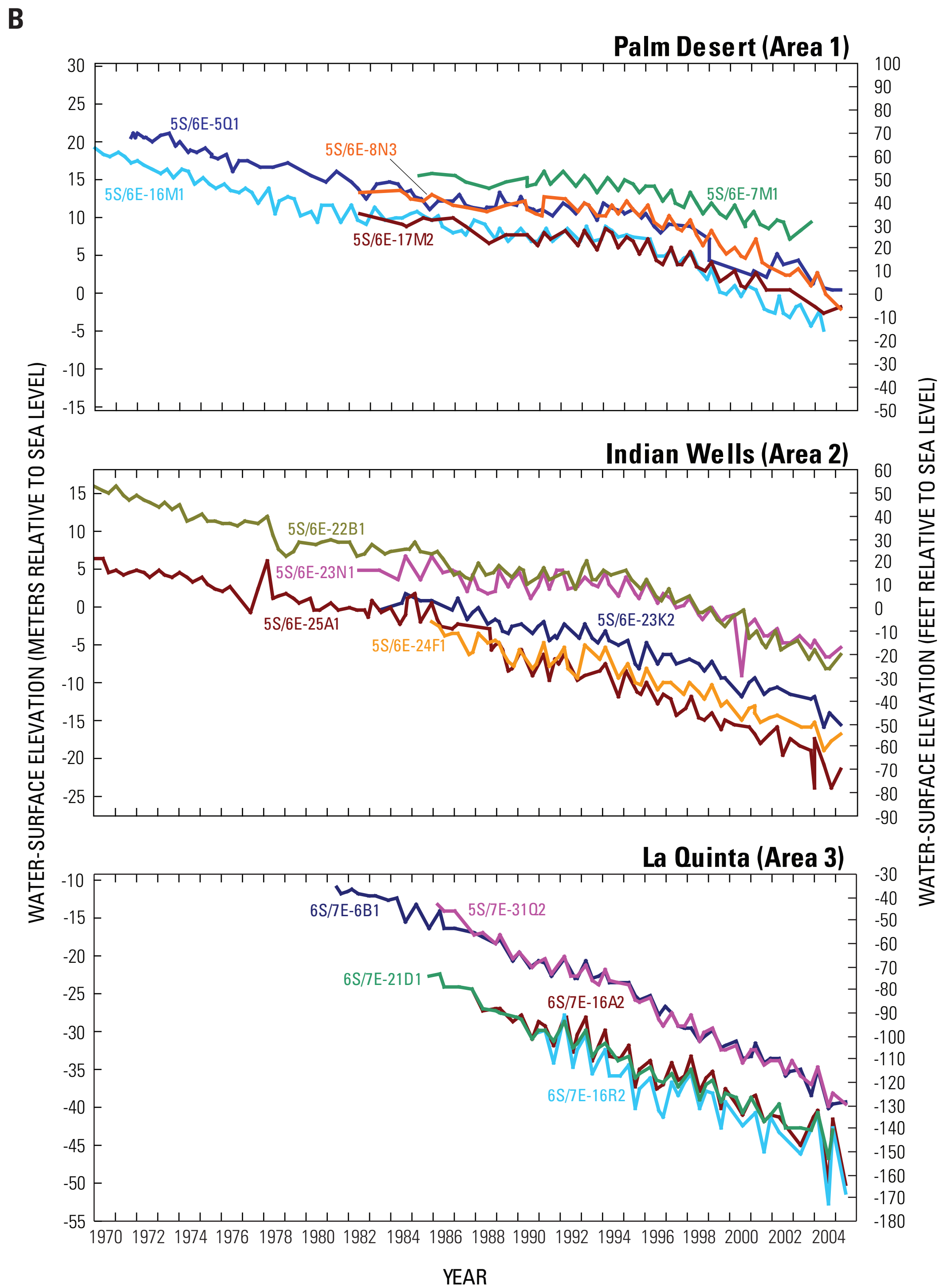

Figure 9. Continued.

In Indian Wells, the areas of subsidence form two separate elongated shapes—one parallel to and one perpendicular to the mountain front. The available water-level data indicate fairly uniform water-level declines in the area, suggesting that the aquifer system is heterogeneous in this part of the valley because sediments responded dissimilarly to similar water-level declines, as exhibited by the irregular shapes of the subsidence areas. Additional evidence of aquifer heterogeneity in the area is given by the distinct northwest-southeast linearity shown on the northern margins of the pair of subsiding bowls, suggesting the presence of barriers to ground-water flow or abrupt changes in lithology that control the northern extent of subsidence (Area 2 in fig. 6).

In La Quinta, water-level data are too sparse to relate to the aquifer-system response, but the northwestern part of the subsiding area has an irregular shape that appears to be related to the contact between the alluvial aquifer and the bedrock basement complex that defines the extent of the aquifer system (Area 3 in figs. 6, 7, 8).

Comparison of InSAR and GPS Results

GPS and InSAR measurements can be compared at monuments MAGF, MANI, and OSDO, and at the CGPS station COTD in Palm Desert (figs. 3, 5, 6, 7, 8). InSAR data are uninterpretable at the other monuments in the land-subsidence monitoring network and at CGPS station TMAP (near S753) because they are in and near agriculturally active areas (which degrades the InSAR data). Because SAR data and GPS data for MAGF, MANI, and OSDO were not collected simultaneously, magnitudes of land subsidence measured by the two methods could not be compared; instead, rates of subsidence were compared at these monuments. Rates of land subsidence that were derived from GPS data measured at GPS monuments were calculated by differencing the ellipsoid heights computed from the GPS surveys in 2000 and 2005 and dividing by 1,813 days—the number of days between August 30, 2000 and August 17, 2005. Rates of land subsidence derived from InSAR data for the locations of GPS monuments were computed by determining the magnitude of land subsidence for each interferogram near each monument, then dividing that magnitude by the number of days that the interferogram spans; 22 subsidence rates (between February 26, 2003 and September 25, 2005) were calculated from the 22 interferograms analyzed. At COTD, absolute magnitudes of subsidence derived from GPS data and InSAR data were compared because continuously collected GPS data permits computation of a position for any day of interest.

At MAGF, 136 mm (0.45 ft) of subsidence was calculated from the GPS data resulting in a calculated subsidence rate of 0.08 mm/d (2.6 x 10^{-4} ft/d). The subsidence rates calculated from InSAR data ranged from 0.06 mm/d to 0.14 mm/d (2.0 x 10^{-4} ft/d to 4.6 x 10^{-4} ft/d); the average calculated subsidence rate was 0.08 mm/d (2.6 x 10^{-4} ft/d) and the standard deviation was 0.03 mm/d (9.8 x 10^{-5} ft/d). At MANI, 78 mm (0.26 ft) of subsidence was calculated from the GPS data resulting in a calculated subsidence rate of 0.04 mm/d (1.3 x 10^{-4} ft/d); the calculated subsidence rates derived from InSAR data ranged from 0 mm/d (0 ft/d) to 0.07 mm/d (2.3 x 10^{-4} ft/d); the average and standard deviation were 0.02 mm/d (6.6 x 10^{-5} ft/d). At OSDO, 203 mm (0.67 ft) of subsidence was calculated from the GPS data resulting in a calculated subsidence rate of 0.11 mm/d (3.6 x 10^{-4} ft/d); the calculated subsidence rates derived from InSAR data ranged from 0.05 mm/d to 0.21 mm/d (1.6 x 10^{-4} ft/d to 6.9 x 10^{-4} ft/d); the average was 0.11 mm/d (3.6 x 10^{-4} ft/d) and the standard deviation was 0.05 mm/d (1.6 x 10^{-4} ft/d).

The coordinates for CGPS station COTD were computed by SOPAC for the dates May 7, 2003, and September 25, 2005, and were compared to the InSAR time series that spans those same dates. GPS observations indicated 24 mm (0.08 ft) of subsidence, while InSAR measurements indicated 25 mm (0.08 ft).

The calculated subsidence rates for monuments MAGF, MANI, OSDO, and the subsidence magnitude at COTD calculated using both GPS data and InSAR data compare favorably, thereby improving confidence in results derived from both methods. The favorable comparison of data for these monuments lends credibility to the GPS data collected at the other monuments in the network where InSAR data is unusable because of incoherence caused by agricultural land use.

Future Monitoring

Continued monitoring in the southern Coachella Valley is warranted because ground-water levels continue to decline to record-low levels in some areas of the valley and, therefore, the significant amounts and rising rates of land subsidence documented by this study are expected to increase. Most of the changes in the vertical positions of the GPS network monuments measured in 1996, 1998, and 2000 were within the measurement errors, indicating that a longer period of time would have been needed to see significant changes. Comparing the land-surface-elevation changes of the monuments in the GPS network in 2005 with those of the previous three surveys did show changes greater than the anticipated GPS measurement errors. As a result, GPS surveys completed every 3-5 years would be sufficient to monitor subsidence rates. Spatially detailed InSAR-derived maps of ground displacements, however, could continue to be processed annually or more frequently depending on data availability, because InSAR can detect relative changes in vertical position as small as 5 mm (0.02 ft) (Hoffmann and others, 2001). Because InSAR-detected areas of subsidence spatially overlap the GPS network, future monitoring of the GPS network could provide ground truth for the more spatially detailed and higher resolution InSAR measurements, as was done during this study. Furthermore, as InSAR technology matures, it is likely that some InSAR measurements made in agriculturally active areas, such as those in the southern Coachella Valley, could result in improved spatial detail of displacement in these areas.

The frequency of water-level measurements in wells in the Coachella Valley is too low to permit meaningful interpretations of the aquifer-system response to water-level changes, particularly when paired with the more frequent InSAR measurements. Furthermore, the wells generally have long or multiple screens such that the water-level measurement is a composite measurement representing a large thickness of the aquifer system. Increasing the measurement frequency of ground-water levels in just a few piezometers (wells constructed with short screens and small diameters for monitoring purposes)—both in areas of known subsidence and in areas of relative stability—would significantly improve analysis of the relationship between changes in water levels and in land-surface elevations. In concert with more frequent water-level measurements, more frequent and high-resolution measurements of aquifer-system compaction, such as those derived from a borehole extensometer, would improve the analysis of aquifer-system response. The information derived from such a monitoring site(s) would be useful in estimating aquifer-system hydraulic parameters that govern ground-water flow and land subsidence. This information could be used to construct a numerical model of ground-water flow and aquifer-system compaction to refine estimates of governing parameters and to predict potential aquifer-system compaction which could be used by CVWD to manage water resources while considering land subsidence.

Summary

Ground water has been a major source of agricultural, municipal, and domestic water supply in the Coachella Valley since the early 1920s. Ground-water levels declined throughout the Coachella Valley from the 1920s until 1949. In 1949, the importation of surface water from the Colorado River to the southern Coachella Valley began, resulting in decreased pumping and a recovery of water levels in some areas. Since the 1970s, the demand for water in the southern Coachella Valley has exceeded the deliveries of the imported surface water, and water levels have again declined. The declining water levels have the potential to induce or renew land subsidence in the Coachella Valley. Results of previous studies by the U.S. Geological Survey indicate that land subsidence may have been as much as about 150 mm (0.5 ft) in the southern parts of the valley between about 1930 and 1996 (Ikehara and others, 1997).

The location and magnitude of vertical land-surface changes during 1996–2005 were determined using GPS and InSAR techniques. The GPS measurements and the images processed for the InSAR measurements described in this report span the area from Palm Desert on the north to the Salton Sea on the south. GPS measurements were more useful than InSAR measurements for determining vertical land-surface changes in agricultural areas, and InSAR measurements were more useful for determining spatially detailed changes in nonagricultural areas. GPS measurements made at 13 geodetic monuments in 1996 and 2005 in the southern Coachella Valley indicate that the elevation of the land surface had a net decline of 333 to 22 mm ±58 mm (1.1 to 0.07 ft ±0.19 ft) during the 9-year period. Changes at 10 of the 13 monuments exceeded the maximum uncertainty of ±58 mm (±0.19 ft) at the 95-percent confidence level indicating that subsidence occurred at these monuments between June 1996 and August 2005. GPS measurements made at 20 geodetic monuments in 2000 and in 2005 indicate that the elevation of the land surface changed –312 to +25 mm ±42 mm (–1.0 to +0.08 ft ±0.14 ft) during the 5-year period. Changes at 14 of the 20 monuments exceeded the maximum uncertainty of ±42 mm (±0.14 ft) at the 95-percent confidence level indicating that subsidence occurred at these monuments between August 2000 and August 2005. Eight of the fourteen monuments for which subsidence rates could be compared indicate that subsidence rates increased by as much as a factor of 10 between 2000 and 2005.

Results of the InSAR measurements made between May 7, 2003, and September 25, 2005, indicate that land subsided about 75 to 180 mm (0.25 to 0.59 ft) in three areas of the Coachella Valley: near Palm Desert, Indian Wells, and La Quinta; the equivalent subsidence rates range from about 3 to more than 6 mm/month (0.01 to 0.02 ft/month). The subsiding areas near these locations were previously identified using InSAR measurements for 1996–2000, which indicated that land subsided about 35 to 150 mm (0.11 to 0.49 ft) during the four-year period; the equivalent subsidence rates range from about 1 to 3 mm/month (0.003 to 0.01 ft/month). Comparison of the InSAR results indicates that subsidence rates have increased by 2 to 4 times since 2000 in these three areas.

Water-level measurements made at wells near the subsiding GPS monuments and near the areas of subsidence shown by InSAR generally indicate that water levels declined during 1996-2005. The relation between declining water levels and significant subsidence may indicate that the water levels have exceeded the preconsolidation stress and that the resulting subsidence may be permanent (inelastic). Continued monitoring in the southern Coachella Valley is warranted because ground-water levels continue to decline to record-low levels in some areas of the valley and, therefore, the significant amounts and increasing rates of land subsidence documented by this study are expected to continue.

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