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# InSAR analysis of natural recharge to define structure of a ground-water basin, San Bernardino, California

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**Abstract.** Using interferometric synthetic aperture radar (InSAR) analysis of ERS-1 and ERS-2 images, we detect several centimeters of uplift during the first half of 1993 in two areas of the San Bernardino ground-water basin of southern California. This uplift correlates with unusually high runoff from the surrounding mountains and increased ground-water levels in nearby wells. The deformation of the land surface identifies the location of faults that restrict ground-water flow, maps the location of recharge, and suggests the areal distribution of fine-grained aquifer materials. Our preliminary results demonstrate that naturally occurring runoff and resultant recharge can be used with interferometric deformation mapping to help define the structure and important hydrogeologic features of a ground-water basin. This approach may be particularly useful in investigations of remote areas with scant ground-based hydrogeologic data.

## 1. Introduction

An aquifer system commonly is a saturated, heterogeneous body of interbedded permeable and poorly permeable hydrogeologic units, called aquifers and aquitards, respectively. Especially in unconsolidated or semi-consolidated deposits, the aquifers and aquitards are linked hydraulically. When ground-water levels decline, often as a result of an increase in ground-water pumping, some support for the overlying material shifts from the pressurized pore fluid to the granular skeleton of the aquifer system, and correspondingly, the land surface subsides. Conversely, when ground water is recharged and ground-water levels rise, some support for the overlying material shifts from the granular skeleton to the pressurized pore fluid, and the skeleton expands [*Galloway et al.*, 1999]. When ground-water levels decline sufficiently so that stress on the aquitards becomes greater than the maximum previous stress (preconsolidation stress), then the aquitards compact and the land surface subsides permanently. Almost all permanent subsidence occurs due to the irreversible (inelastic) compression or consolidation of aquitards. Recoverable (elastic) subsidence can occur in both aquifers and aquitards [*Tolman and Poland*, 1940].

Traditional hydrogeologic investigations have relied on expensive, ground-based data collection to define important characteristics of an aquifer system. Commonly, a large number of wells are needed to define the extent of the aquifer system, the effectiveness of all lateral boundaries, and the location of internal barriers to ground-water flow. An equivalent effort in surface-water monitoring is required to define the amount and location of recharge. Remote-sensing techniques—such as aerial photography and aeromagnetic, gravimetric, and seismic surveys—sometimes are employed to aid in mapping the geologic deposits and in inferring the extent and hydrogeologic characteristics of the aquifer system.

InSAR utilizes two or more coherent phase signals acquired at different times for the same land area to map changes in range (satellite to earth distance) at a spatial resolution of tens of meters and a vertical accuracy of centimeters [*Massonnet and Feigl*, 1998]. InSAR analysis of an aquifer system involves mapping and analyzing the surface deformation caused by hydrogeologic processes [e.g., *Amelung et al.*, 1999; *Galloway et al.*, 1998; *Massonnet et al.*, 1997]. In general, this kind of analysis has been prompted by historical land subsidence caused by ground-water pumpage. In this paper we show that InSAR is equally useful in helping to characterize an aquifer system by analyzing the land-surface inflation caused by naturally occurring recharge. It may be possible to short-circuit some of the expensive, time-consuming traditional data collection and analysis if InSAR is used initially or concurrently with other methods.

## 2. Study Area

The San Bernardino area of southern California (Fig. 1) was chosen to demonstrate this use of InSAR because it has been studied extensively and is monitored continuously with surface-water gages and ground-water wells. The area lies between the northwest-trending San Andreas and San Jacinto Faults, and is bounded by the impermeable granitic rocks of the San Bernardino and San Gabriel Mountains, by the sedimentary rocks of the Badlands, and by the low, east-facing escarpment of the San Jacinto Fault [*Dutcher and Garrett*, 1963]. The area includes two ground-water subbasins, Lytle Creek and Bunker Hill, which are filled with unconsolidated alluvial deposits that comprise the aquifer system. Runoff from the surrounding mountains fills several intermittently flowing streams including the two largest, the Santa Ana River and Lytle Creek.

In this semi-arid region, ground-water levels rise and fall dramatically in response to recharge from the intermittently flowing streams. During a period of low runoff and extensive ground-water extractions from about 1950 to 1970, ground-

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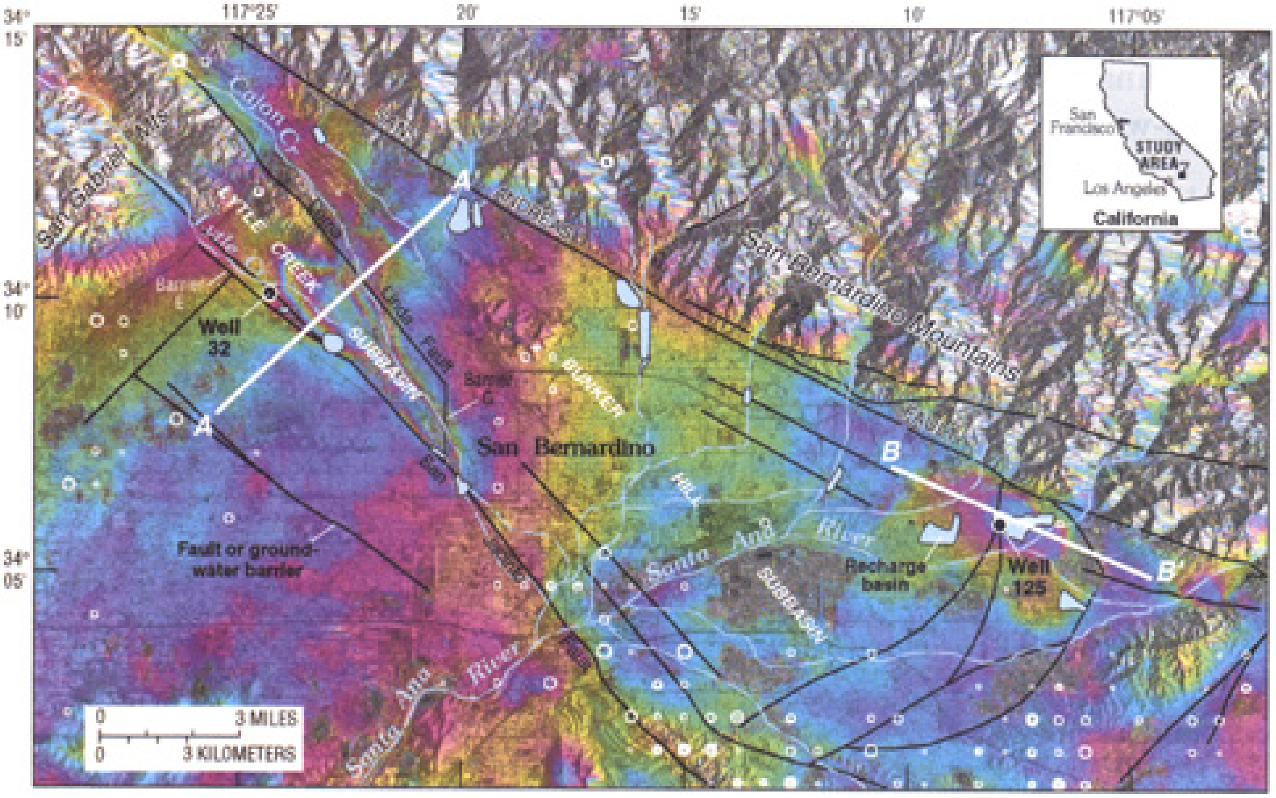

**Figure 1.** SAR interferogram of land-surface deformation over the San Bernardino area, California, during the period from December 25, 1992, to August 27, 1993. Uplifts of about 7 cm and 3 cm are indicated by concentric color patterns in the middle of sections A-A' and B-B', respectively. Earthquake epicenters (white circles) were obtained from the South California Earthquake Information Center.

water levels fell as much as 50 m and induced land subsidence of as much as 30 cm in the area where the Santa Ana River crosses the San Jacinto Fault [*Miller and Singer*, 1971]. After 1970, both natural and artificial recharge increased so that by 1980, ground-water levels in that part of the basin had risen to within a meter of land surface.

## 3. InSAR Observations

To study land-surface deformation in the San Bernardino area, we used InSAR techniques with imagery acquired by the European Space Agency (ESA) ERS-1 and ERS-2 satellites. In this preliminary analysis, we used a total of 13 SAR images for the period April 24, 1992, to December 2, 1995, obtained from the Western North America InSAR Consortium (WInSAR) archive. We used a 2-pass InSAR method [*Massonnet and Feigl*, 1998] to produce the land-surface deformation map. The digital elevation model (DEM) used in the processing is from the U.S. Geological Survey (USGS) 7.5-minute map data, which has a horizontal resolution of 30 m and a specified vertical accuracy of 7 m RMS. Ten interferograms were produced in this preliminary analysis of

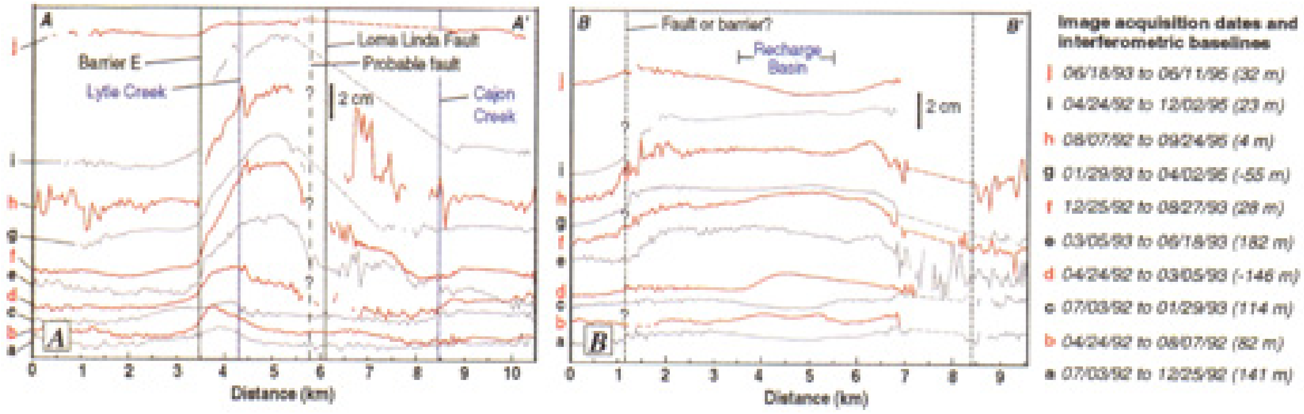

**Figure 2.** Land-surface deformation for section A-A' (Lytle Creek area) and B-B' (Santa Ana River area) is shown for selected periods. Magnitude of deformation (range change) during each period is indicated by 2 cm bar. Locations of sections are shown in Figure 1.

the San Bernardino area. Baselines of the SAR images range from 14 to 180 m, indicating that the interferograms are relatively insensitive to errors in the DEM. Interferometric coherence is well maintained over most of the ground-water subbasins for as long as three years.

The most striking feature we found is shown in an interferogram constructed with SAR images acquired on December 25, 1992, and August 27, 1993 (Fig. 1). Each fringe represents a range change of 2.83 cm along the satellite look direction (23° from the vertical), which corresponds to 3.07 cm of vertical deformation. A total range shortening of about 6 cm, which corresponds to about 7 cm of uplift, occurred in the Lytle Creek area between two bounding faults during the 8-month interval.

To confirm that the fringes in Fig. 1 were not caused by the atmospheric delay anomaly [e.g., *Lu et al.*, 2000], we formed another interferogram spanning the time interval of March 5 to June 18, 1993 (http://edc.usgs.gov/images/lu_insar1.jpg). About 1.5 fringes were observed, which corresponds to range shortening of about 4 cm, or an uplift of 4.3 cm during these three and one-half months. The amount of deformation for this period constitutes about two-thirds of the deformation observed in Fig. 1. Those two images were acquired at different times than the images used in preparing Fig. 1; therefore, atmospheric anomalies did not contribute a significant part of the observed deformation. Another interferogram constructed using images acquired on April 24, 1992, and March 5, 1993, shows about 2 cm of range shortening (2.2 cm of uplift) over the area (http://edc.usgs.gov/images/lu_insar2.jpg).

To systematically study the observed deformation, we generated another seven interferograms. The range changes for these interferograms and those in Fig. 1 are shown along a profile through the Lytle Creek area (Figs. 1 and 2a). From this InSAR analysis, the following can be observed.

1. The deformation field is elongated northwest-southeast, which aligns with the orientation of streams (Lytle Creek and Cajon Creek). This shape suggests that stream recharge may be responsible for the observed uplift.

2. The deformation is restricted mostly to the area between the two bounding faults (San Jacinto and Loma Linda). The northeastern end of the deformation field extends beyond the Loma Linda Fault and seems to be aligned with Cajon Creek. The southwestern end of the deformation extends beyond ground-water Barrier *G*, which suggests that the barrier may be located approximately or that it may be only partly restrictive. The extent of the deformation before March 5, 1993, covered a much smaller area. It seems to be constrained by the San Jacinto Fault and by a ground-water barrier located between the San Jacinto and Loma Linda Faults, and most likely is related to recharge from Lytle Creek.

3. The land surface deformed significantly during the 3.5 months from March 5 to June 18, 1993. During this period, there was about a 4-cm range change (curve e in Fig. 2a), while only about a 2-cm range change occurred during the immediately preceding period from April 24, 1992, to March 5, 1993 (curve d in Fig. 2a).

4. The deformation did not dissipate significantly in the next two to three years. Curves g, h, and i in Fig. 2a suggest that the uplift that occurred during the first half of 1993 persisted to the end of 1995. A range change of more than 6 cm was observed from several interferograms spanning 1992 and 1995 (curves g, h, and i in Fig. 2a). We observed only about ±0.5 cm of land-surface deformation from June 18, 1993, to June 11, 1995 (curve j in Fig. 2a).

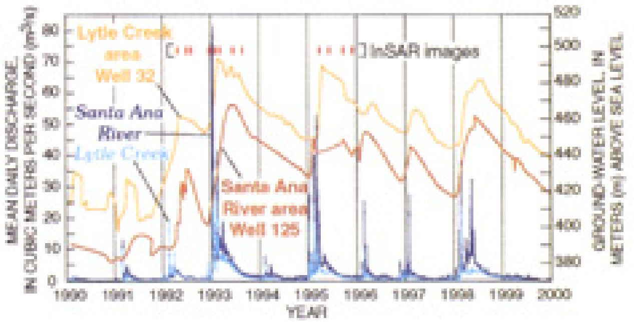

**Figure 3.** Discharge in Lytle Creek and the Santa Ana River, and ground-water levels in the vicinity of Lytle Creek (well 32) and the Santa Ana River (well 125). High discharges in 1993 produced a rise in ground-water levels in both wells. InSAR image acquisition dates are denoted.

5. The shape of curves g, h, and i in Fig. 2a mimics the shape of curves a–f. Therefore, most of the deformation shown in curves g, h, and i in Fig. 2a depicts ground-surface movement that occurred during the first half of 1993. Because InSAR data were not available from August 1993 to April 1995 it is uncertain whether the inflation that occurred in 1993 persisted continuously through 1995, or whether it may have dissipated and reoccurred prior to April 1995.

We also systematically studied land-surface deformation where the Santa Ana River flows out of the San Bernardino Mountains (Fig. 1). Deformation in this area (Fig. 2b) is shown using a 10-km profile for the same times as shown in Fig. 2a. Between December 25, 1992, and August 27, 1993, there was about a 3-cm range change (3.3 cm uplift), two-thirds of which occurred between March 5 and June 18, 1993. This result and ratio is similar to the deformation observed for the Lytle Creek area (Fig. 2a). We similarly found that the deformation persisted to the end of 1995.

## 4. Discussion

Is the inflation tectonic? The observed uplift occurred northwest of Barrier *E* and the San Jacinto Fault, which is a right-lateral, strike-slip fault like other faults subparallel to the San Andreas Fault. It therefore is possible that tectonic forces squeezed the area between the San Jacinto and Loma Linda Faults, causing the uplift. The interferometric patterns, however, suggest that this mechanism is unlikely. There is no comparable inflation or deflation southwest of Barrier E such as might be expected if tectonic movement created different pressures on the aquifer skeleton, causing an upward movement of the land surface. Rather, response of the land surface appears to be restricted to the area east of the San Jacinto Fault. *Amelung et al.* [1999] made similar observations for the Las Vegas Valley, where the spatial extent of subsidence is controlled by faults. It also is possible that earthquakes could have caused the observed inflation. The areal distribution of earthquakes that were detected during the period of the uplift, however, does not appear to coincide with the interferometric patterns (Fig. 1). It is possible that tectonic stress not evidenced by earthquakes played a role in the observed response of the land surface.

Is the inflation caused by ground-water recharge? Compared to previous years, 1993 had unusually large amounts of runoff in both Lytle Creek and the Santa Ana River as measured at gaging stations (Fig. 3). During high-runoff years, considerable recharge occurs in the San Bernardino area, as evidenced by rapidly rising ground-water levels (Fig. 3). Hydrographs of wells near each of the observed areas of land-surface uplift show a similar temporal pattern of rising ground-water levels that coincide with the rising land-surface altitude. Therefore, it seems likely that most of the approximately 4–7 cm increase in land-surface altitude observed near the upper reaches of Lytle Creek and the Santa Ana River was caused by ground-water recharge that occurred as a result of high runoff during the first half of 1993. The lack of InSAR data for 1994 makes the analysis of the intervening period between 1993 and 1995 difficult. However, it seems reasonable to suggest that the land surface probably partially deflated during 1994 when ground-water levels declined, then re-inflated during the relatively high runoff period of 1995.

During the period 1992–93, the rise in land-surface altitude compared to the rise in ground-water levels ranged from 0.003 to 0.005 in the Lytle Creek area, and from 0.0006 to 0.0008 in the Santa Ana River area. These values represent the component of the aquifer storage coefficient caused by compressibility of the aquifer skeleton. Values on the order of 0.0005 are typical for the elastic storage coefficient of an alluvial basin [*Galloway et al.*, 1998]. Values on the order of 0.005 would be typical of an inelastic storage coefficient, which presumably is involved only during subsidence of the land surface. The higher storage coefficients in the Lytle Creek area—0.003 for the period 12/25/92 to 8/27/93 and 0.005 for the period 3/5/93 to 6/18/93—may be caused by a higher percentage of fine-grained materials or possibly by different antecedent conditions resulting from runoff in 1992 (Fig. 3). The higher values might also be affected by entrapment of air within the aquifer, a characteristic of rapid recharge. Water surveyors in the San Bernardino area noted increased degassing of air from production wells during this 1992–95 time period. Based on these observations of land-surface inflation, the thickness of saturated, compressible settlements in the San Ana River area during 1992-93 is about 150 m.

In the Lytle Creek area, a nearly equivalent increase in ground-water levels to that observed in 1993 began in early 1992. Based on findings from the InSAR ground-water level analyses, it seems reasonable to assume that the total land-surface inflation during 1992 might have been equivalent to that observed in 1993 (7 cm). Therefore, the total increase for the two-year period (1992–93) could have been as much as 14 cm. Based on elastic response of the aquifer system, this inflation is likely to be transitory and would be expected to dissipate as ground-water levels declined after 1995.

The pattern of inflation shown on the interferogram is helpful in identifying the structure of the ground-water basin. Inflation in the Lytle Creek area clearly identifies the bounding faults of the Lytle Creek subbasin (Fig. 1). In contrast, inflation in the Santa Ana River area shows no such linear features and is highly symmetric, emanating from the uppermost of two recharge basins near the Santa Ana River. The pattern of inflation also can suggest the type and distribution of aquifer materials. The elliptic response of inflation in the Santa Ana River area suggests a relatively uniform geologic deposit is present along the base of the mountains. Most likely this is the near-surface alluvial fan deposit.

In general, the land-surface response in the Santa Ana River area is more diffuse than in the Lytle Creek area, perhaps suggesting that coarser aquifer materials are present in the Santa Ana River area. This suggestion correlates with our estimates of the elastic response in the Santa Ana River area being lower. The southern edge of the elliptic inflation in the Santa Ana River area suggests that some change in aquifer materials or structure occurs about 3 km south of the recharge pond. The scalloped edge of the fringe might indicate a change in the subsurface that is not evident in surficial geologic deposits or stream courses. Further refinement of these observations will require ground-based data collection.

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