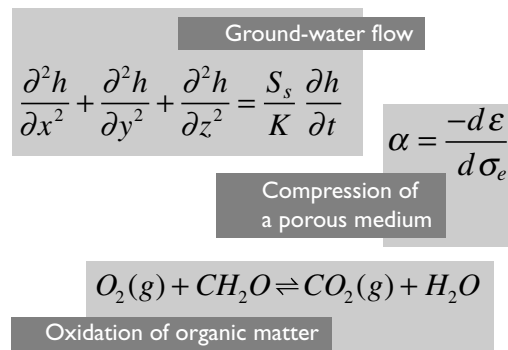# THE ROLE OF SCIENCE

Land Subsidence in the United States

Scientists use equations that represent physical and chemical processes to analyze subsidence.

Ground-water flow

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S_s}{K}\frac{\partial h}{\partial t}$$

$$\alpha = \frac{-d\varepsilon}{d\sigma_e}$$

Compression of a porous medium

$$O_2(g) + CH_2O \rightleftharpoons CO_2(g) + H_2O$$

Oxidation of organic matter

Devin Galloway, S.E. Ingebritsen, and Francis S. Riley
U.S. Geological Survey,
Menlo Park, California

Marti E. Ikehara
National Geodetic Survey,
Sacramento, California

Michael C. Carpenter
U.S. Geological Survey,
Tucson, Arizona

The Panel on Land Subsidence of the U.S. National Research Council (NRC) (1991) recognized three information needs: *"First, basic earth-science data and information on the magnitude and distribution of subsidence [...] to **recognize** and to **assess** future problems. These data […] help not only to address local subsidence problems but to identify national problems. [...] Second, **research on subsidence processes** and engineering methods for dealing with subsidence […] for cost-effective damage prevention or control. […] And third, although many types of **mitigation** methods are in use in the United States, studies of their cost-effectiveness would facilitate choices by decision makers."* (emphases added)

The third need can only be met after we learn how to better measure the total impact of subsidence problems and the effectiveness of our attempted solutions. It is clear that in order to assess the total impact we would need to inventory the total costs to society of overdrafting susceptible aquifer systems. Presently this is impractical because there are only sparse estimates of subsidence costs, and most of these are directly related to damages to tangible property. Additional consideration could be given to many of the indirect costs of excessive ground-water withdrawal and subsidence. In particular, it is our impression that the impact of subsidence on our surface-water resources and drainage—riparian and wetland habitat, drainage infrastructure, and flood risk—is large. Though much knowledge could be gained from risk-benefit analyses that include the indirect costs of subsidence, in this concluding chapter we focus on the role of science as identified by the NRC panel—recognition and assessment of subsidence, research on subsidence processes, and mitigation methods.

RECOGNITION

The occurrence of land subsidence is seldom as obvious as it is in the case of catastrophic sinkholes such as those in Winter Park, Florida, or at the Retsof Salt Mine in Genesee Valley, New York. Dis-

covery of such catastrophic subsidence is difficult only when the localized collapse occurs in a remote area. Where ground-water mining or drainage of organic soils are involved, the subsidence is typically gradual and widespread, and its discovery becomes an exercise in detection. Gazing out over the San Joaquin Valley, California, one would be hard-pressed to recognize that more than 30 feet of subsidence has occurred in some locations. In the absence of obvious clues such as protruding wells, failed well casings, broken pipelines, and drainage reversals, repeat measurements of land-surface elevation are needed to reveal the subsidence.

The problem of detection in regional land subsidence is compounded by the large areal scale of the elevation changes and the requirement for vertically stable reference marks—bench marks—located outside the area affected by subsidence. Where such stable bench marks exist and repeat surveys are made, subsidence is fairly easily measured using professional surveying instruments and methods. In fact, this is one of the common ways in which subsidence is first detected. Often, public agencies or private contractors discover that key local bench marks have moved only after repeat surveys that span several years or longer. Prior to the discovery, when the cumulative subsidence magnitude is small, the apparent errors in the surveys may be adjusted throughout the network under the assumption that the discrepancies reflect random errors of the particular survey. The subsidence may then go undetected until later routine surveys, or until suspicions arise and steps are taken to confirm the current elevations of the affected bench marks.

Subsidence is sometimes obvious

Protruding well casings are common in agricultural areas and some urban areas where ground water has been extracted from alluvial aquifer systems. The land surface and aquifer system are displaced downward relative to the well casing, which is generally anchored at a depth where there is less compaction. The stressed well casings are subject to failure through collapse and dislocation. Submersible pumps, pump columns, and the well itself may be damaged or require rehabilitation. Deep wells are most vulnerable and are also the most expensive to repair and replace. Typical repair costs amount to $5,000–$25,000 or more, and replacement costs are in the range of $40,000–$250,000! Where the frequency of well-casing failures is high, land subsidence is often suspected and is often the cause.

The formation of earth fissures in alluvial aquifer systems is another indication that compaction and land subsidence may be occurring. Other possible indicators of land subsidence include changes in flood-inundation frequency and distribution; stagnation or reversals of streams, aqueducts, storm drainages, or sewer lines; failure, overtopping or reduction in freeboard along reaches of levees, canals, and flood-conveyance structures; and, more generally, cracks and/or changes in the gradient of linear engineered structures such as pipelines and roadways.
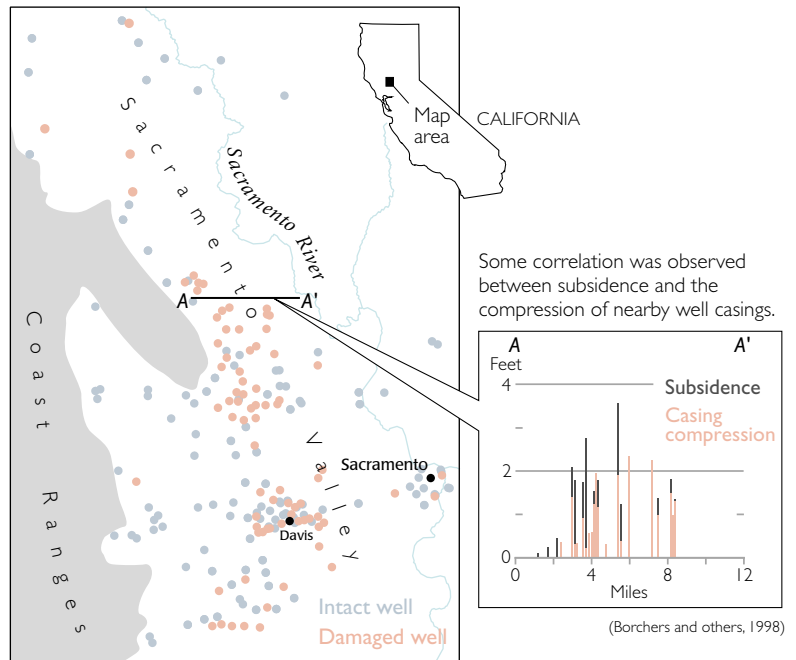

Well head

Subsidence

(Pictured is Terry Katzer)
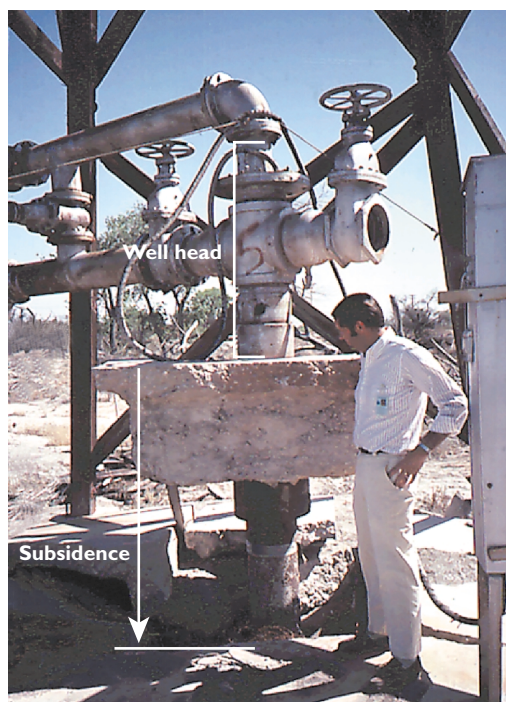
An abandoned water-supply well protrudes above ground in Las Vegas, 1997.

Drought conditions in the Sacramento Valley during 1976-77 reduced the amount of surface water available for irrigation and, for the first time, more ground water than surface water was used to irrigate crops.

During the summer of 1977 many irrigation wells that penetrated the valley-fill deposits were damaged. Most of the damaged wells occurred in the southwestern part of the valley. The damage seems to have been caused by compaction of the aquifer system which resulted in the vertical compression and rupture of well casings.

Some correlation was observed between subsidence and the compression of nearby well casings.

Intact well
Damaged well

(Borchers and others, 1998)

This bench mark was established in 1995 to monitor potential land subsidence in the Antelope Valley, Mojave Desert, California.

ASSESSMENT

Differential surveys measure relative changes in the position of the land surface. The observable position is typically a geodetic mark that has been established to some depth (usually greater than 10 feet when in soil), so that any movement can be attributed to deep-seated ground movement and not to surficial effects such as frost heave. Sometimes geodetic marks, especially those used to measure vertical movement (bench marks), are established in massive artificial foundations, such as bridge abutments, that are well-coupled to the earth. Any vertical or horizontal movement of a geodetic mark is measured in relation to other observation points. When the bench mark can be assumed to be stable or its movement is otherwise known and measurable, it can be used as a control point, and the absolute position of the observation point can be determined. By this method, land subsidence has been measured using repeat surveys of bench marks referenced to some known, or presumed stable, reference frame. Access to a stable reference frame is essential for the measurements needed to map land subsidence. In many areas where subsidence has been recognized, and other areas where subsidence has not yet been well documented, accurate assessment has been hindered or delayed by the lack of a sufficiently stable vertical reference frame (control).
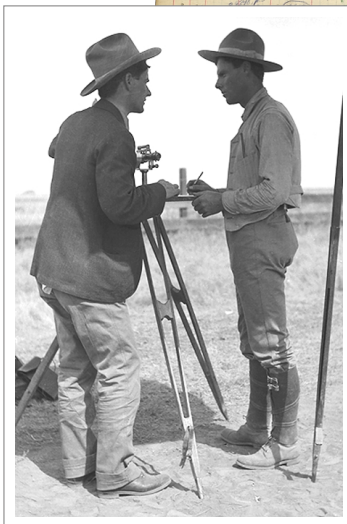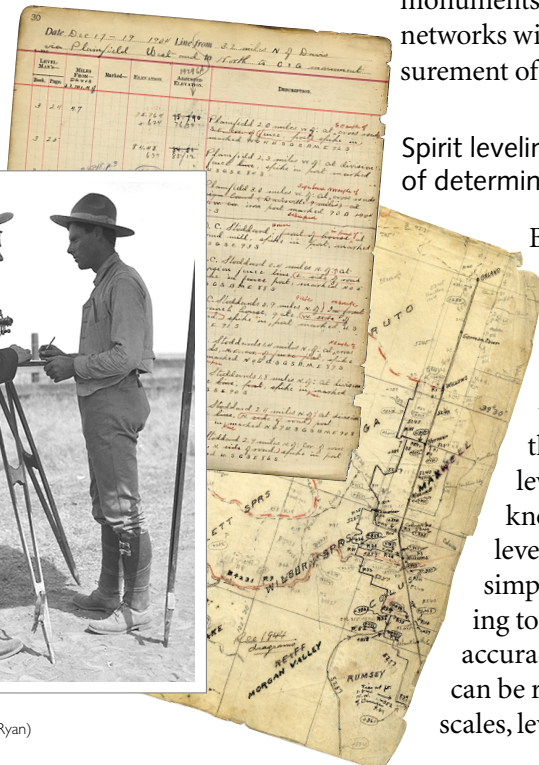
Known positions are linked into a network

"Sufficiently stable" is a somewhat relative term that has meaning in the context of a particular time-frame of interest and magnitude of differential movement. Because of continuous and episodic crustal

motions caused mostly by postglacial rebound, tectonism, volcanism, and anthropogenic alteration of the Earth's surface, it is occasionally necessary to remeasure geodetic control on a national scale. Networks of geodetic control consist of known positions that are determined relative to a horizontal or vertical datum or both.

Two reference networks are used for horizontal and vertical geodetic control for the United States, the North American Datum of 1983 (NAD83) and the North American Vertical Datum of 1988 (NAVD88). NAD83 replaces the older North American Datum of 1927 (NAD27) and is the current geodetic reference system for horizontal control in the United States, Canada, Mexico, and Central America. It is the legally recognized horizontal control datum for the Federal government of the United States and for 44 of the 50 individual States. NAVD88 replaces the National Geodetic Vertical Datum of 1929 (NGVD 1929), which was based on local mean sea levels determined at 26 tidal gauges. The principal sea-level reference for NAVD88 is the primary tidal gauge at Father Point/Rimouski, Quebec, Canada. The vertical datum is based on the Earth's geoid—a measurable and calculable surface that is equivalent to mean sea level.
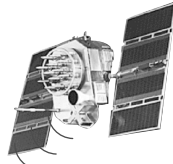
In partnership with other public and private parties, the National Geodetic Survey (NGS) has implemented High Accuracy Reference Networks (HARNs) in every State. HARN observation campaigns (originating in Tennessee in 1986 and ending in Indiana in 1997) resulted in the establishment of some 16,000 survey stations. The updated networks were needed not only to replace thousands of historic bench marks and horizontal-control marks lost to development, vandalism, and natural causes, but also to provide geodetic monuments easily accessible by roadways. These updated reference networks will facilitate the early and accurate detection and measurement of land subsidence.

Spirit leveling was once a common method of determining elevation

Before the advent of the satellite-based Global Positioning System (GPS) in the 1980s, the most common means of conducting land surveys involved either the theodolite or, since the 1950s, the geodimeter (an electronic distance measuring device, or EDM). If only vertical position were sought, the spirit level has been the instrument of choice. The technique of differential leveling allows the surveyor to carry an elevation from a known reference point to other points by use of a precisely leveled telescope and graduated vertical rods. Despite its simplicity, this method can be very accurate. When surveying to meet the standards set for even the lower orders of accuracy in geodetic leveling, 0.05-foot changes in elevation can be routinely measured over distances of miles. At large scales, leveling and EDM measurement errors increase. When

For more information on geodetic control, visit the National Geodetic Survey web site at **http://www.ngs.noaa.gov/faq.shtml**

USGS survey party spirit leveling near Colusa, Sacramento Valley, in 1904 and their field notes.

(John Ryan, donated courtesy of Thomas E. Ryan)

the scale of the survey is small (on the order of 5 miles or less) and the desired spatial density is high, spirit leveling is still commonly used because it is accurate and relatively inexpensive. Large regional networks warrant use of the more efficient Global Positioning System (GPS) surveying for differential surveys.

GPS—Global Positioning System uses Earth-orbiting satellites

A revolution in surveying and measurement of crustal motion occurred in the early 1980s when tests of the satellite-based NAVSTAR GPS showed that it was possible to obtain 1 part in 1 million precision between points spaced from 5 to more than 25 miles apart. GPS uses Earth-orbiting satellites to trilaterate positions based on the time required for radio signals transmitted from satellites to reach a receiving antenna. An accurate three-dimensional position can be determined from trilateration of the range distances between the receiver and at least four satellites. Since July 17, 1995, NAVSTAR has been operational with a full constellation of 24 satellites, and in North America provides essentially continuous coverage with at least 6 satellites in view. Guidelines have been formulated for establishing GPS-derived ellipsoid heights with accuracy standards at either the 2-cm (.0656 ft) or the 5-cm (.164 ft) level (Zilkoski and others, 1997).

In land-subsidence and other crustal-motion surveys, the relative positions of two points can be determined when two GPS receivers, one at each observation point, receive signals simultaneously from the same set of 4 or more satellites. When the same points are reoccupied following some time interval, any relative motion between the points that occurred during the time interval can be measured. Geodetic networks of points can be surveyed in this fashion. Such a network, one of the first of its kind designed specifically to monitor land subsidence, was established in the Antelope Valley, Mojave

A full constellation of the Global Positioning System (GPS) includes 24 satellites in orbit 12,500 miles above the Earth. The satellites are positioned so that we can receive signals from six of them at any one time from any point on the Earth.
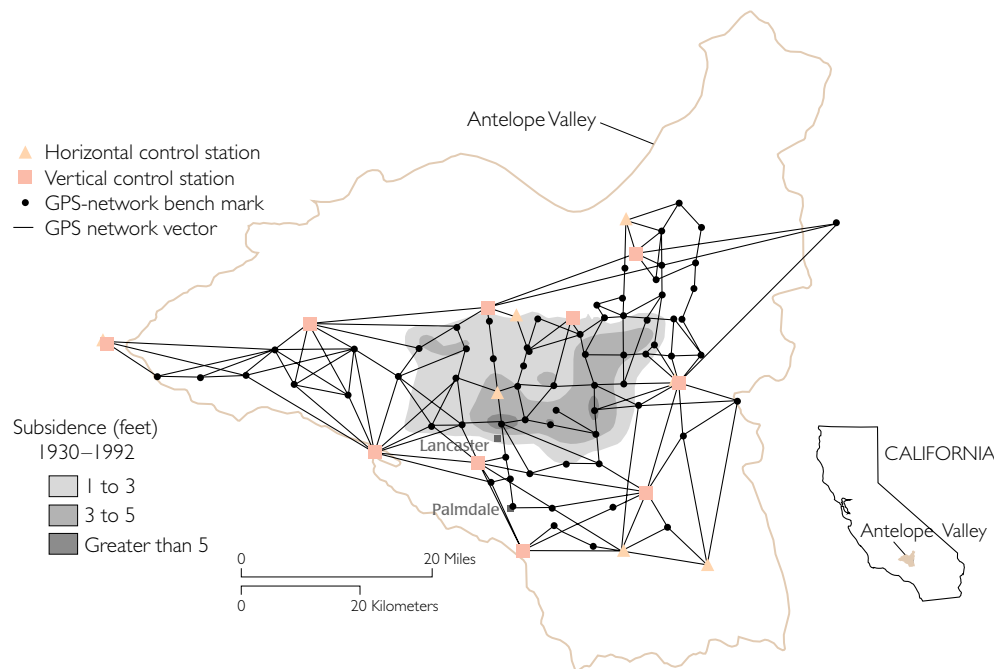

(Jay Prendergast, 1992)

A GPS antenna mounted on a tripod at a known distance above a geodetic mark near Monterey, California, receives signals from GPS satellites. The operator is entering station information into a receiver that stores the signals for later processing.

- ▲ Horizontal control station
- ■ Vertical control station
- • GPS-network bench mark
- — GPS network vector

Antelope Valley

Lancaster

Palmdale

Subsidence (feet)
1930–1992
- ☐ 1 to 3
- ☐ 3 to 5
- ☐ Greater than 5

0   20 Miles

0   20 Kilometers

CALIFORNIA

Antelope Valley

This geodetic network was used to measure historical subsidence in Antelope Valley, Mojave Desert, California.

Geodetic surveying of 85 stations in Antelope Valley using GPS required about 150 person-days during 35 days of observation in 1992. Results from the GPS surveys and conventional leveling surveys spanning more than 60 years showed a maximum subsidence of about 6.6 feet; more than 200 square miles had subsided more than 2 feet since about 1930 (Ikehara and Phillips, 1994).
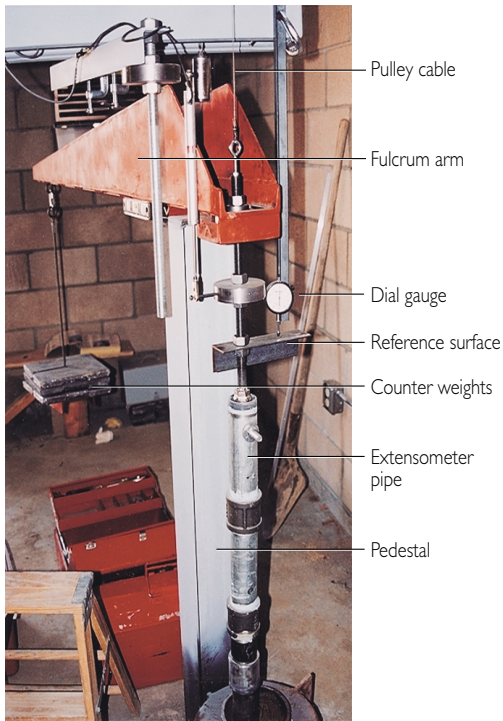
Part of a two-stage
counter-weighted pipe ex-
tensometer that measures
compaction in a shallow
aquifer near Lancaster,

Desert, California in 1992 (Ikehara and Phillips, 1994). It was de-
signed to determine the subsidence of previously leveled bench
marks and enable precise measurement of points separated by tens
of miles for future subsidence monitoring. Other large GPS-based
geodetic networks for subsidence monitoring have been established
in Albuquerque, New Mexico; the Avra Valley, Arizona; Las Vegas,
Nevada; the Lower Coachella Valley, California; the Sacramento-San
Joaquin Delta, California; and the Tucson basin, Arizona. GPS sur-
veying is also a versatile exploratory tool that can be used in a rapid
mode to quickly but coarsely define subsidence regions, in order to
site more precise, site-specific and time-continuous measurement
devices such as extensometers.

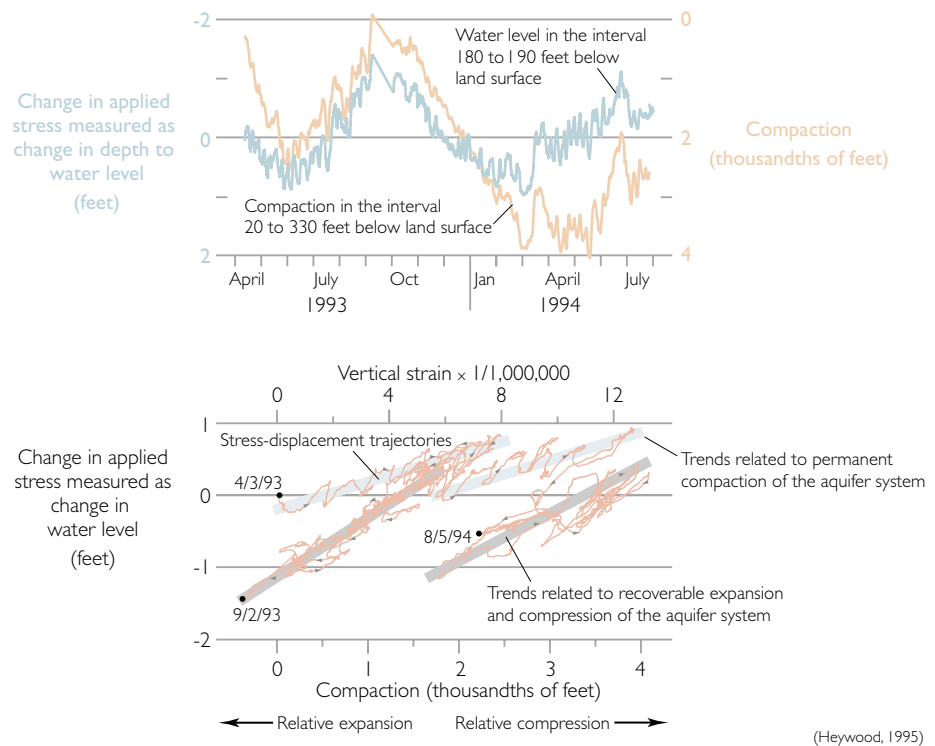## Extensometers measure subsidence and horizontal displacement

Borehole extensometers generate a continuous record of change in
vertical distance between the land surface and a reference point or
"subsurface bench mark" at the bottom of a deep borehole (Riley,
1986). In areas undergoing aquifer-system compaction, the exten-
someter is the most effective means of determining precise, continu-
ous deformation at a point. If the subsurface bench mark is
established below the base of the compacting aquifer system, the
extensometer can be used as the stable reference or starting point for
local geodetic surveys. Designs that incorporate multiple-stage ex-
tensometers in a single instrument are being used to measure aqui-
fer-system compaction simultaneously in different depth intervals.

This two-stage, counter-
weighted pipe extensometer
measures compaction simulta-
neously in shallow and deep
aquifers in Antelope Valley,
Mojave Desert, California.

As the aquifer system com-
presses, the land surface sub-
sides along with the exten-
someter table. The
extensometer pipe anchored
deeper in the aquifer system
appears to rise relative to the
table. This relative movement
represents the amount of verti-
cal displacement occurring in
the aquifer system between
the shallow-seated piers sup-
porting the table and the bot-
tom of the extensometer pipe.
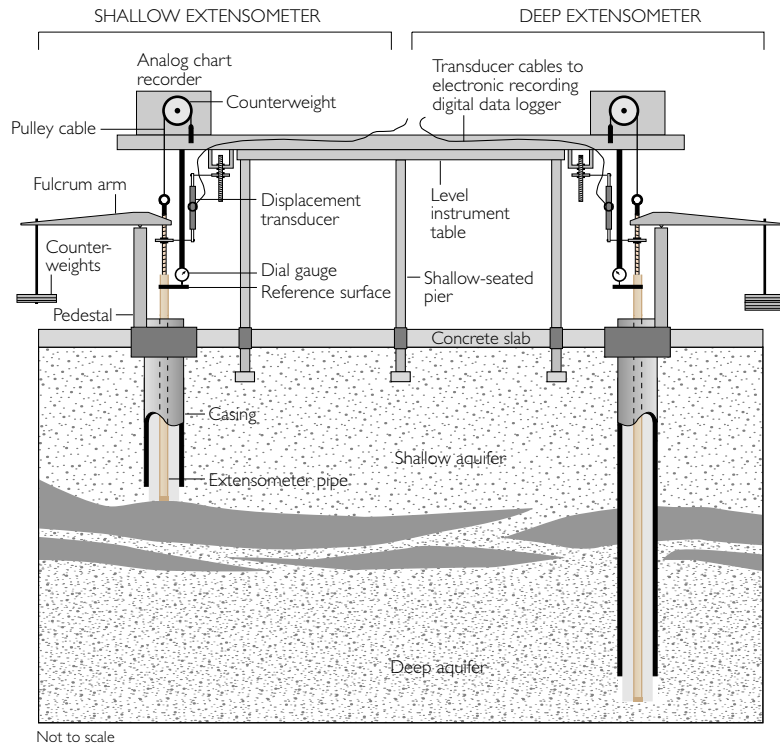
Measurements of water level and compaction from borehole extensometers form the basis of stress-strain analysis. These data are from the Hueco Basin, El Paso, Texas.

Change in applied stress measured as change in depth to water level (feet)

Water level in the interval 180 to 190 feet below land surface

Compaction (thousandths of feet)

Compaction in the interval 20 to 330 feet below land surface

April   July   Oct   Jan   April   July
1993   1994

Vertical strain × 1/1,000,000

Change in applied stress measured as change in water level (feet)

Stress-displacement trajectories

4/3/93

8/5/94

9/2/93

Trends related to permanent compaction of the aquifer system

Trends related to recoverable expansion and compression of the aquifer system

Compaction (thousandths of feet)

← Relative expansion   Relative compression →

(Heywood, 1995)

This quartz-tube horizontal extensometer is being installed near Apache Junction, Arizona. The quartz tube is placed inside the pipe housing and attached to a post on one side of a fissure. A displacement sensor, such as a dial gage, is attached to the post on the opposite side of the fissure and pushes against the quartz tube. Fissure opening and closing is observed in the dial-gage reading. An electronic sensor can be substituted for the dial gage for continuous measurement of fissure movement.
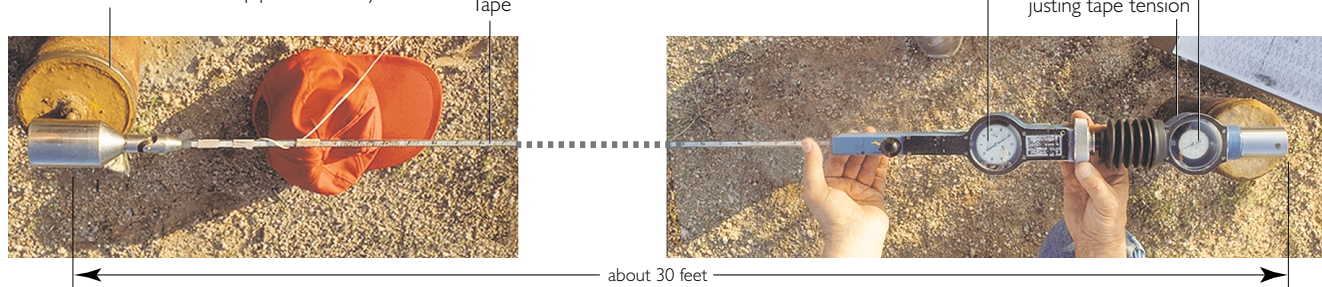

Pipe housing

Quartz tube

Post
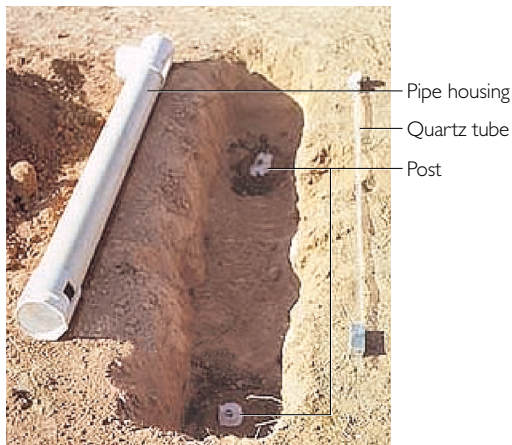
As a stand-alone instrument, the borehole extensometer may be regarded simply as a sentinel against the undetected onset of unacceptable rates of aquifer-system compaction. However, when used in conjunction with good well logs and water-level data from an adjacent observation well, the deformation history generated by an extensometer can provide the basis for stress-strain analysis (Riley, 1969) and inverse modeling that defines the average compressibility and vertical hydraulic conductivity of the aquitards (Helm, 1975). This capability derives from the fact that the compaction measured by the extensometer is directly related to the volume of water produced by the aquitards. Major improvements in stability and sensitivity allow recently constructed extensometers to record the minute elastic compression and expansion that inevitably accompany even very small fluctuations in ground-water levels in unconsolidated alluvial aquifer systems, as well as the relatively large deformations typical of the irreversible compaction of aquitards. Reliable estimates of aquitard properties are necessary for constraining predictive modeling, whether the objective is the prevention or mitigation of land subsidence or simply the optimal use of the storage capacity of the aquifer system.

Several kinds of horizontal extensometers measure differential horizontal ground motion at earth fissures caused by changes in ground-water levels (Carpenter, 1993). Buried horizontal extensometers constructed of quartz tubes or invar wires are useful when precise, continuous measurements are required on a scale of 10 to 100 feet. Tape extensometers measure changes across intermonument distances up to 100 feet with a repeatability of 0.01 inches. The tape

The extensometer is attached at both ends to a monument (yellow cylinder), which is a 10-foot rod driven into the ground and encased with a concrete-filled pipe for stability.

Tape

Dial gage for measurement along tape

Dial gage for tape tension

Proving ring for adjusting tape tension

← about 30 feet →

Tape extensometers measure horizontal ground motion over distances of up to 100 feet.

extensometer is used in conjunction with geodetic monuments specially equipped with ball-bearing instrument mounts, which can serve as both horizontal and vertical control points. Arrays or lines of monuments can be extended for arbitrary distances, usually in the range of 200 to 600 feet.
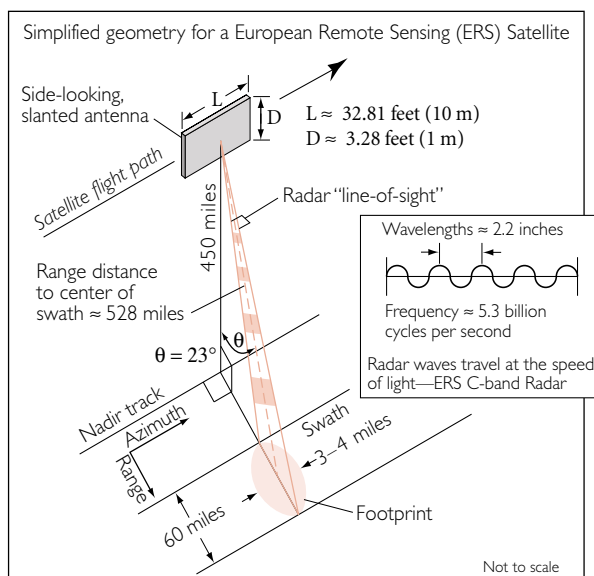
Radar interferometry is a new tool for measuring subsidence

Interferometric Synthetic Aperture Radar (InSAR) is a powerful new tool that uses radar signals to measure deformation of the Earth's crust at an unprecedented level of spatial detail and high degree of measurement resolution. Geophysical applications of radar interferometry take advantage of the phase component of reflected radar signals to measure apparent changes in the range distance of the land surface (Gabriel and others, 1989; Massonnet

Radar* is an active sensor, transmitting a signal of electromagnetic energy. Satellite-borne radar using one antenna transmits a pulsed train of microwaves.

The waves reflect off the ground surface, and echoes are received by the moving antenna, producing a recorded image of the scanned ground that is continuous along the track of the satellite and about 60 miles wide.

The restricted size of the satellite antenna limits the spatial resolution to 3 to 6 miles on the ground.

*RADAR: RAdio Detection And Ranging

Simplified geometry for a European Remote Sensing (ERS) Satellite

Side-looking, slanted antenna

L

D

$L \approx 32.81$ feet (10 m)
$D \approx 3.28$ feet (1 m)

Satellite flight path

Radar "line-of-sight"

450 miles

Range distance to center of swath ≈ 528 miles

Wavelengths ≈ 2.2 inches

Frequency ≈ 5.3 billion cycles per second

Radar waves travel at the speed of light—ERS C-band Radar

$\theta = 23°$ θ

Nadir track

Azimuth

Range

Swath
3–4 miles

60 miles

Footprint

Not to scale

Synthetic Aperture Radar (SAR) imaging can "synthesize" an effectively larger antenna (about 3 miles long) with a spatial resolution on the order of 16 feet by pulsing the microwaves every 16 feet of satellite travel.

The 3- to 4-mile-wide footprints overlapped at 16-foot intervals along the ground track are processed through a technique similar to medical x-ray imaging. Numerous 16-foot echoes are averaged to improve signal coherence, and the actual spatial resolution is on the order of 260 feet or better.

Interferograms are made by differencing successive SAR images taken from the same orbital position but at different times. Under favorable radiometric conditions 1/2-inch to 1/10-inch resolution is possible in the line-of-sight (range) of the radar.

and Feigl, 1998). Ordinary radar on a typical Earth-orbiting satellite has a very poor ground resolution of about 3–4 miles because of the restricted size of the antenna on the satellite. Synthetic Aperture Radar (SAR) takes advantage of the motion of the spacecraft along its orbital track to mathematically reconstruct (synthesize) an operationally larger antenna and yield high-spatial-resolution imaging capability on the order of tens of feet. The size of a picture element (pixel) on a typical SAR image made from satellite-borne radar may be as small as 1,000 square feet or as large as 100,000 square feet, depending how the image is processed.

For landscapes with more or less stable radar reflectors (such as buildings or other engineered structures, or undisturbed rocks and ground surfaces) over a period of time, it is possible to make high-precision measurements of the change in the position of the reflectors by subtracting or "interfering" two radar scans made of the same area at different times. This is the principle behind InSAR.

Under ideal conditions, it is possible to resolve changes in elevation on the order of 0.4 inches (10 mm) or less at the scale of 1 pixel. Interferograms, formed from patterns of interference between the phase components of two radar scans made from nearly the same antenna position (viewing angle) but at different times, have demonstrated dramatic potential for high-density spatial mapping of ground-surface deformations associated with tectonic (Massonnet and others, 1993; Zebker and others, 1994) and volcanic strains (Massonnet and others, 1995; Rosen and others, 1996; Wicks and
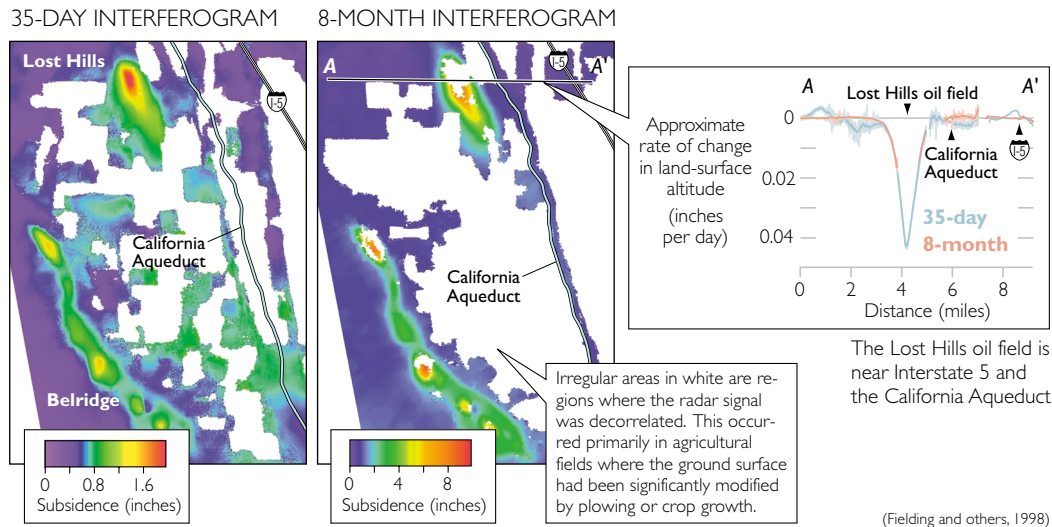

Differential interferogram made from InSAR images acquired June 1993 and March 1997 over the Tucson and Green Valley areas of Arizona. The interferogram (center) is shown overlain on the radar amplitude image.

One color cycle represents about 1.1 inch of subsidence. More than two cycles can be seen on this Tucson image.

Increasing relative subsidence

0   4 Miles

0   4 Kilometers
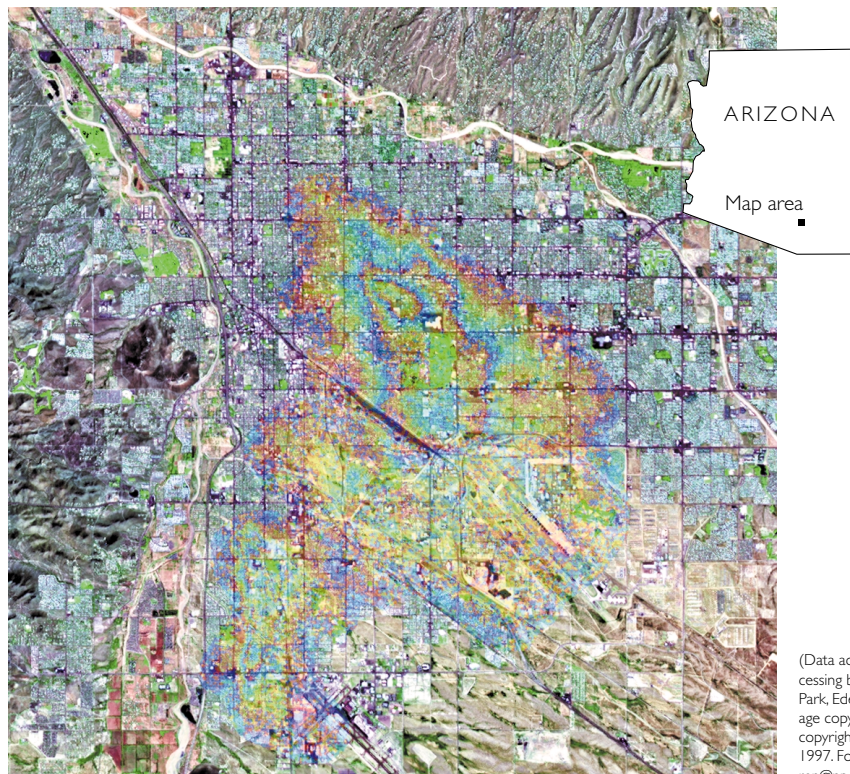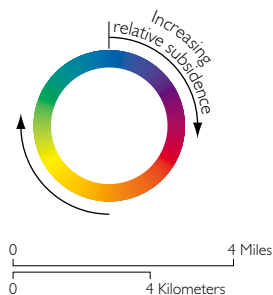
(Data acquisition and interferometric processing by the NPA Group, Crockham Park, Edenbridge, Kent TN8 6SR, UK. Image copyright: NPA 1998. Image data copyright: European Space Agency 1993, 1997. For information contact ren@npagroup.co.uk)

Extraction of oil, brine, and ground water from the Lost Hills and Belridge oil reservoirs in the San Joaquin Valley, California, caused compaction, forming surface subsidence bowls. Near Lost Hills more than 1.5 inches of subsidence occurred in 35 days and nearly 3 inches occurred in 8 months.

35-DAY INTERFEROGRAM

8-MONTH INTERFEROGRAM

CALIFORNIA

Map area

Irregular areas in white are regions where the radar signal was decorrelated. This occurred primarily in agricultural fields where the ground surface had been significantly modified by plowing or crop growth.

The Lost Hills oil field is near Interstate 5 and the California Aqueduct.

(Fielding and others, 1998)

others, 1998). InSAR has also recently been used to map localized crustal deformation and land subsidence associated with geothermal fields in Imperial Valley, California (Massonnet and others, 1997), Long Valley, California (W. Thatcher, USGS, written communication, 1997), and Iceland (Vadon and Sigmundsson, 1997), and with oil and gas fields in the Central Valley, California (Fielding and others, 1998). InSAR has also been used to map regional-scale land subsidence caused by aquifer-system compaction in the Antelope Valley, California (Galloway and others, 1998), Las Vegas Valley, Ne-

Different methods of measuring land subsidence

METHOD	Component displacement	Resolution[1] (milimeters)	Spatial density[2] (samples/survey)	Spatial scale (elements)
Spirit level	vertical	0.1–1	10–100	line-network
Geodimeter	horizontal	1	10–100	line-network
Borehole extensometer	vertical	0.01–0.1	1–3	point
Horizontal extensometer:				
Tape	horizontal	0.3	1–10	line-array
Invar wire	horizontal	0.0001	1	line
Quartz tube	horizontal	0.00001	1	line
GPS	vertical horizontal	20 5	10–100	network
InSAR	range	10	100,000– 10,000,000	map pixel[3]

[1]Measurement resolution attainable under optimum conditions. Values are given in metric units to conform with standard geodetic guidelines. (One inch is equal to 25.4 millimeters and 1 foot is equal to 304.8 millimeters.)

[2]Number of measurements generally necessary to define the distribution and magnitude of land subsidence at the scale of the survey.

[3]A pixel on an InSAR displacement map is typically 40 to 80 meters square on the ground.

vada (Amelung and others, 1999), and Santa Clara Valley, California (Ikehara and others, 1998).
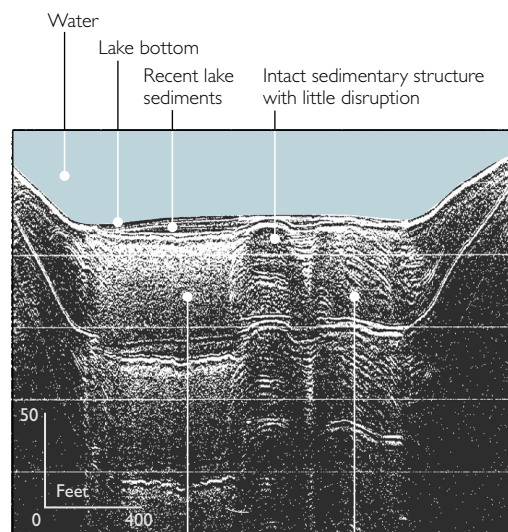
RESEARCH ON SUBSIDENCE PROCESSES

The areal and vertical distribution of subsidence-prone materials, their current state of stress, and their stress history govern the potential for subsidence. These factors vary in importance and can be determined with varying degrees of difficulty for the three major types of subsidence considered in this Circular.

In the case of organic-soil subsidence (oxidation), the subsidence-prone material is generally surficial, and both thickness and areal extent are often readily mapped. The state of stress and the stress history are largely irrelevant, as the subsidence rate is mainly determined by the degree of drainage. In aquifer-system compaction, the subsidence-prone (fine-grained) material is buried and must be mapped indirectly by drilling, sampling, assembling drilling logs of the subsurface lithology, and by various borehole and surface geophysical techniques. These methods produce spatially discrete information—often one-dimensional or, in the case of surface geophysics, quasi-two dimensional with integrated depth information. The interpretation is often ambiguous and extrapolation of the spatially limited data to other areas of interest is laden with uncertainty, making the mapping imperfect. Mapping of subsidence-prone materials is perhaps most difficult for those materials subject to catastrophic collapse, because the failures are so localized and frequently evolve over short time scales. Acoustic profiling has been used successfully to map possible locations of buried cavities in west-central Florida. For both aquifer-system compaction and cavity collapse, the current stress and stress history are critically important.

An acoustic profile taken across a sinkhole lake in west-central Florida shows how high-resolution seismic-reflection techniques can image geologic characteristics associated with subsidence.

(Tihansky and others, 1996)

Water

Lake bottom

Recent lake sediments

Intact sedimentary structure with little disruption

50

Feet

0   400

Units have failed or have been disrupted, leaving little identifiable geologic structure.

Dipping reflectors along margins of buried cavities where geologic units are deformed and are sagging into underlying void space

In typical alluvial ground-water basins, an accurate initial estimate of preconsolidation stress (critical head) is particularly important for successful evaluation of the historical compaction of aquifer systems (Hanson, 1989; Hanson and Benedict, 1994). Prior to the development of ground-water resources in a basin, the alluvial sediments are typically overconsolidated—the initial preconsolidation stress of the aquifer system is larger than the intergranular or effective stresses. Land subsidence becomes obvious only after substantial water-level drawdowns have caused increased intergranular stresses and initiated inelastic compaction. Holzer (1981) identified a variety of natural mechanisms that can cause such an overconsolidated condition in alluvial basins, including removal of overburden by erosion, prehistoric ground-water-level declines, desiccation, and diagenesis. Few investigations have examined the elastic responses of the aquifer system to changes in effective stress under natural conditions, before large-scale ground-water withdrawal has begun to cause irreversible subsidence. As a result, information on critical aquifer hydraulic head, representing the native preconsolidation stress of the system, is usually deduced from paired time-series of ground-water levels and land subsidence (Holzer,1981; Anderson, 1988,1989) measured at wells and nearby bench marks, or inferred from ground-water-flow models (Hanson and others, 1990; Hanson and Benedict, 1994).

Similar uncertainties exist for systems that have undergone some period of lowered ground-water levels and land subsidence followed by ground-water-level recovery and slowing or cessation of subsidence. The problem of determining the new preconsolidation stress thresholds in these aquifer systems is equally as difficult as determining the native preconsolidation stresses in undeveloped aquifer systems. The difficulty is compounded when the developed aquifer systems contain thick aquitards affected by hydrodynamic lag.

Preconsolidation stress is usually deduced from paired time-series of ground-water levels and subsidence. Estimates of preconsolidation stress such as these from Antelope Valley, Mojave Desert, California, are used to evaluate the historical compaction of aquifer systems.
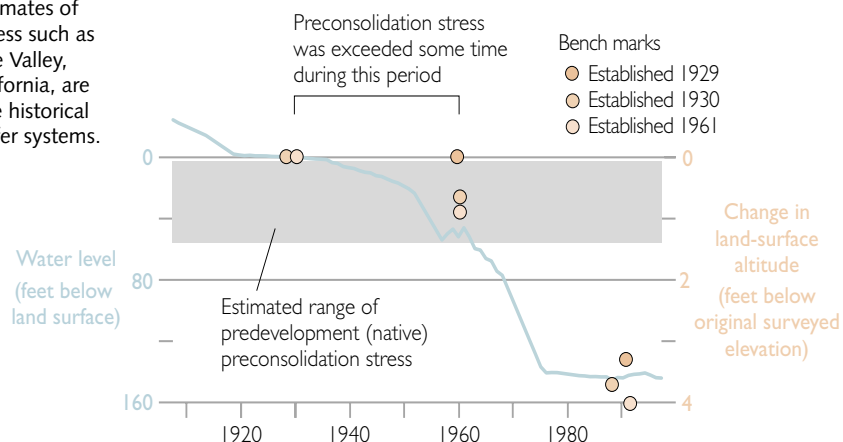
This three-layer digital model of Antelope Valley, Mojave Desert, California is a mathematical representation of the physical processes of ground-water flow and aquifer-system compaction. Separate model layers represent different depth horizons within the aquifer system. Flow and compaction properties are specified for each of the 2,083 active cells in the model.

The computer model solves for hydraulic head for each cell and computes ground-water fluxes between cells and within individual cells between the elastic and inelastic storage components. These values are then used to calculate the amount of compaction, if any, for each cell. The total amount of compaction in all three layers is the computed land subsidence at that location.

Differences between measured and simulated compaction and water levels are minimized through a history-matching process. Model parameters are iteratively adjusted to find the best match between simulated and measured values. Once the set of possible model parameters is constrained by the history match, the model may be used cautiously to predict future land subsidence.

In this example, 18 sites were used to match water levels and 10 sites were used to match compaction; one of each is shown.
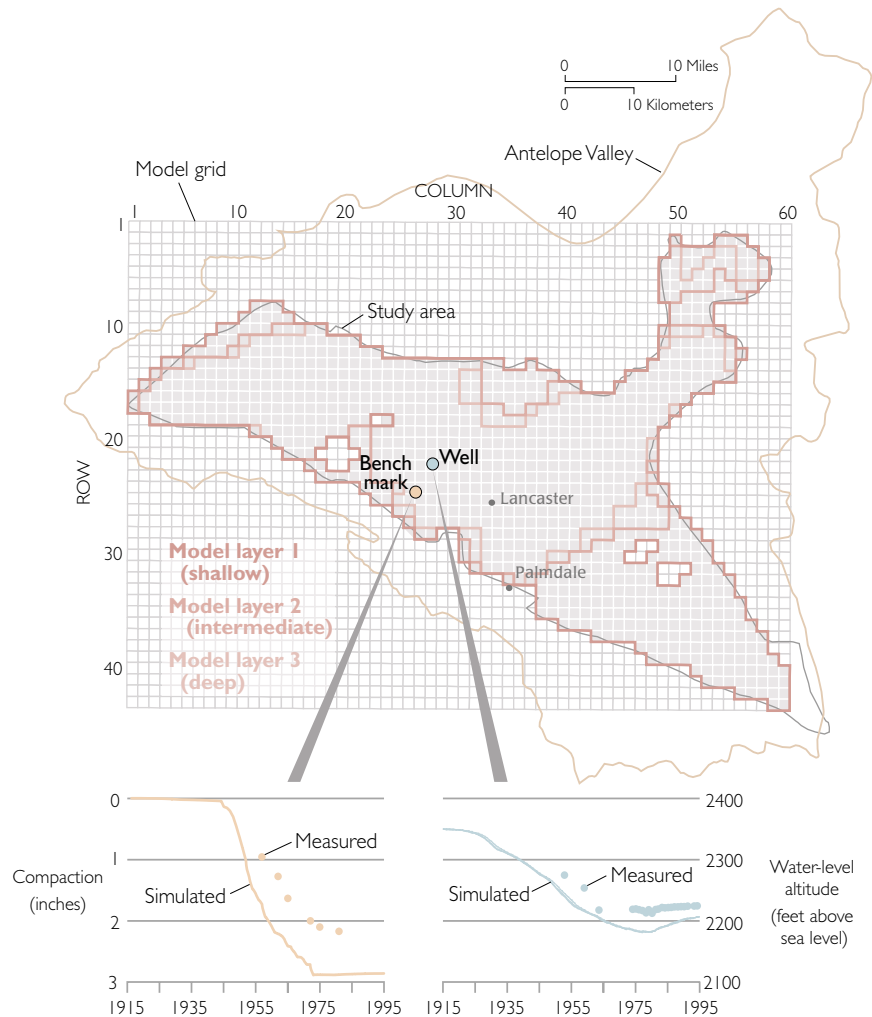
Simulation models are useful analytical tools

Since the advent of high-speed digital computers, scientists have had the ability to numerically simulate the flow of ground water and associated aquifer-system compaction in multiple dimensions. In actual practice, ground-water flow may be simulated in one, two, or three dimensions, but compaction is typically simulated as a one-dimensional process (Helm, 1978). Though poroelastic theory developed by Biot (1941) provides a means for coupling ground-water flow and skeletal deformation in three dimensions, scientists commonly invoke the one-dimensional theory of hydrodynamic consolidation developed by Terzaghi (1925), which is described in some detail in the introduction to the section on "Mining Ground Water." Multidimensional flow of ground water is described by a variant of the well-known diffusion equation that also describes conduction of heat and electricity.
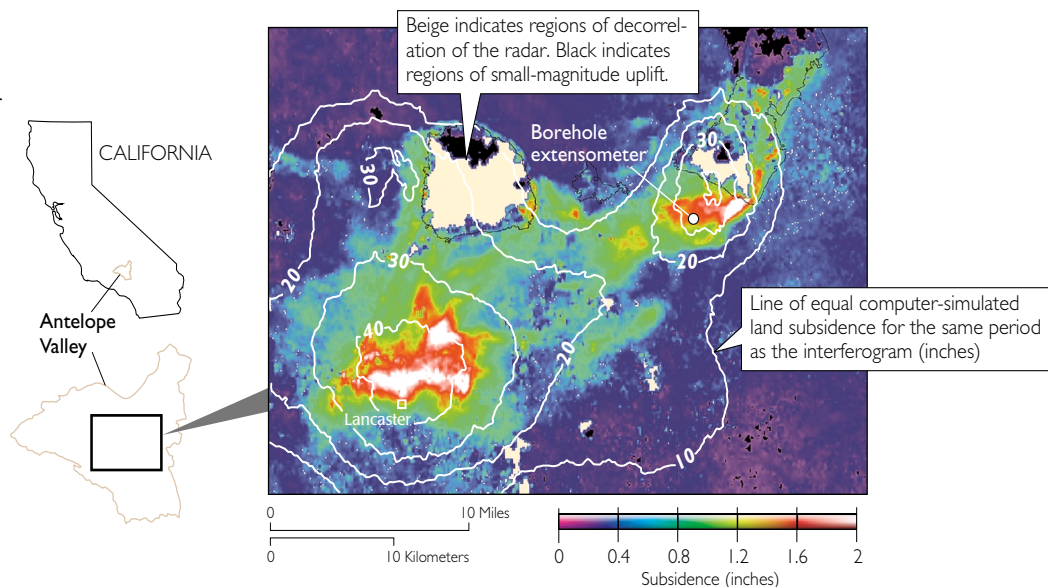
Simulation models can aid visualization of complex three-dimensional processes. They are important analytical tools, and can also be used to help devise data-acquisition and water-management strategies. Though simulation models are powerful tools, it is im-
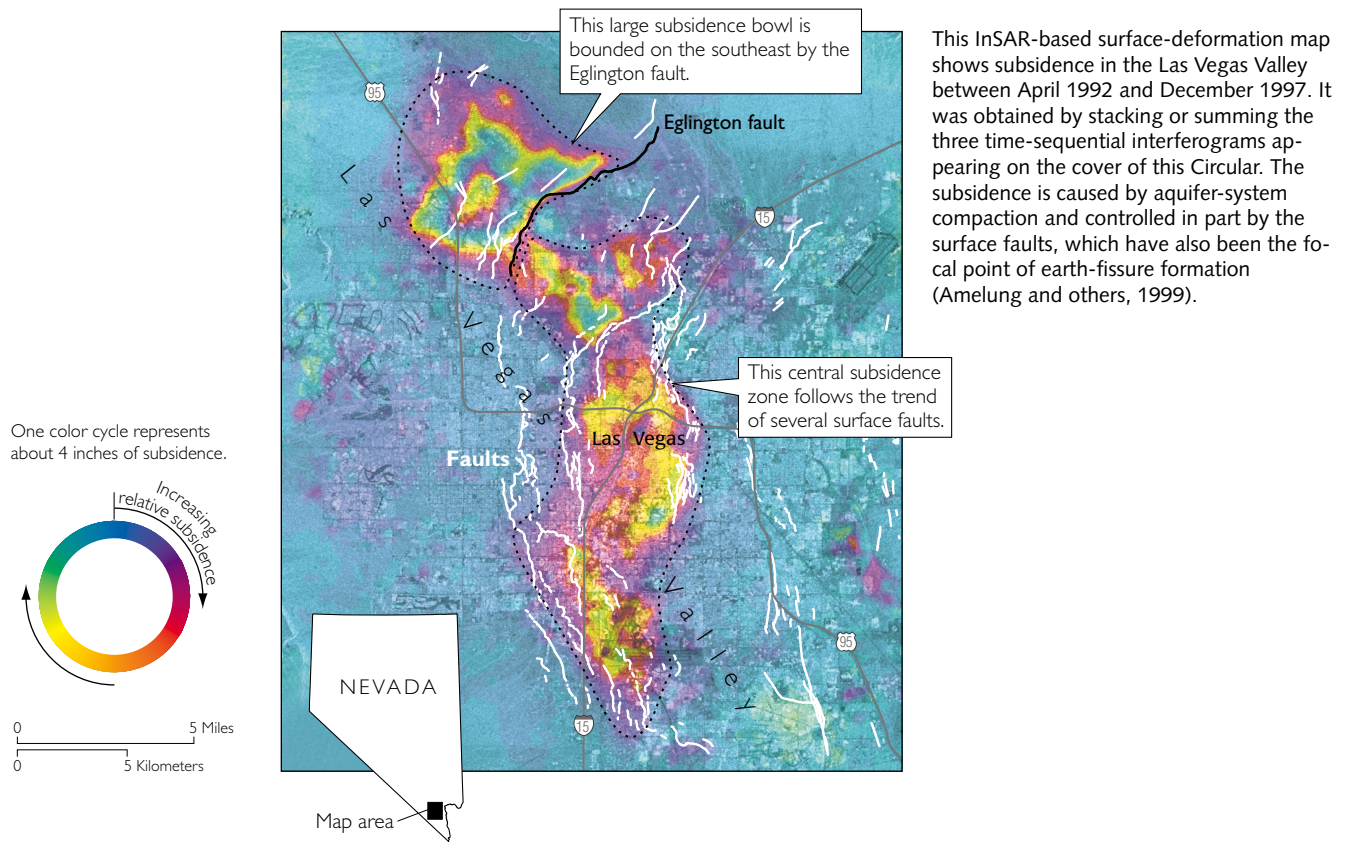
portant to recognize their limitations. The common assumption of one-dimensional consolidation is motivated by an obvious truism: most aquifer-system compaction takes place in the vertical dimension. Nevertheless, the widespread occurrence of earth fissures indicates that horizontal deformation can be locally significant. A more general and more important limitation of simulation models is that their solutions are nonunique. The relevant hydrogeologic parameters (permeabilities, compressibilities, and boundary conditions) are never exactly known, which would be required for a unique solution. Nevertheless, simulation models may be used—with caution—in a predictive mode, and there are formal procedures for dealing with parameter uncertainties.

InSAR images offer new insights

In the Antelope Valley, Mojave Desert, California, a radar interferogram for the period October 20, 1993 to December 22, 1995 revealed up to 2 inches of subsidence in areas previously affected by as much as 6 feet of subsidence since 1930 (Galloway and others, 1998). The regions of maximum subsidence detected during the 26-month period correlated well with declining ground-water levels. In another part of Antelope Valley formerly affected by ground-water depletion and subsidence, but where ground-water levels recovered throughout the 1990s, about 1 inch of subsidence was detected on the interferogram. This suggests residual (time-delayed) compaction due to the presence of thick aquitards. Computer simulations of aquifer-system compaction compared favorably with the subsidence detected by the interferogram for the same period. The computer simulation was weakly constrained due to the scarcity of conventional field measurements; these results highlight the potential use of spatially detailed InSAR subsidence measurements to provide better constraints for computer simulations of land subsidence.

Simulated and InSAR-detected land subsidence in the Antelope Valley are compared for the time period October 1993–December 1995.

This large subsidence bowl is bounded on the southeast by the Eglington fault.

Eglington fault

This InSAR-based surface-deformation map shows subsidence in the Las Vegas Valley between April 1992 and December 1997. It was obtained by stacking or summing the three time-sequential interferograms appearing on the cover of this Circular. The subsidence is caused by aquifer-system compaction and controlled in part by the surface faults, which have also been the focal point of earth-fissure formation (Amelung and others, 1999).

This central subsidence zone follows the trend of several surface faults.

Las Vegas

Faults

One color cycle represents about 4 inches of subsidence.

Increasing relative subsidence
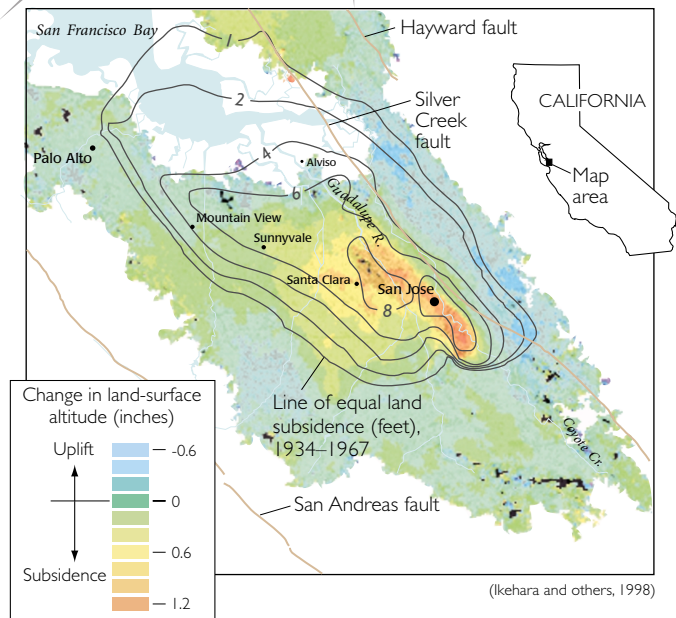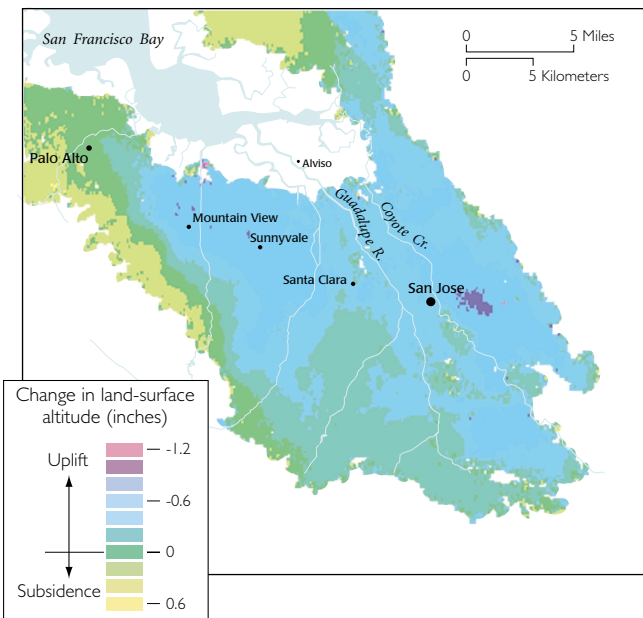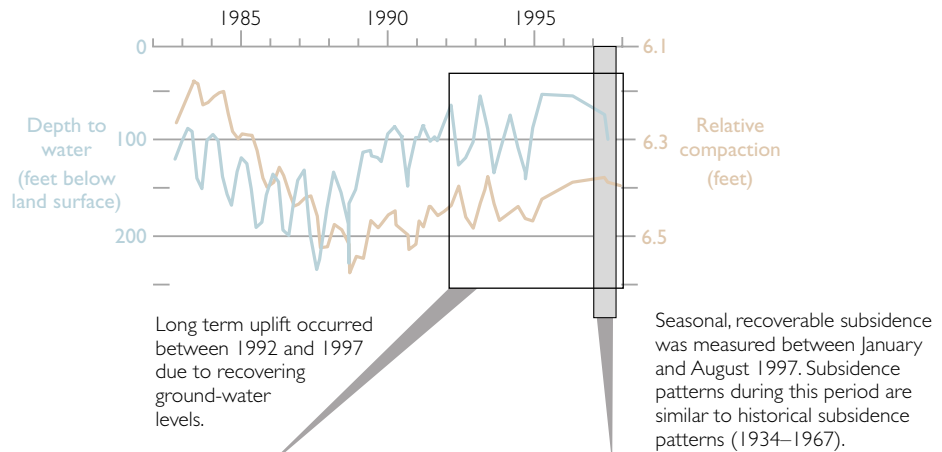
0   5 Miles
0   5 Kilometers

NEVADA

Map area

New InSAR-based surface-deformation maps for Las Vegas Valley demonstrate the intimate connection between faults and subsidence. An interferogram for the Las Vegas Valley between April 21, 1992, and December 5, 1997, delineates two main features—a subsidence bowl in the northwest and an elongated subsiding zone in the central part of the valley. The northwest subsidence bowl is nearly circular along its western extent and includes the area of maximum subsidence of nearly 7.5 inches. Its southeastern boundary is aligned along the Eglington scarp, one of several Quaternary faults cutting the valley-floor alluvium. Little subsidence is detected immediately southeast of the fault. Similarly, the central subsidence zone follows the general trends of several mapped faults. The map suggests that the spatial distribution of land subsidence in Las Vegas Valley is controlled by Quaternary faults to a much greater degree than previously suspected. The faults may separate compressible from less-compressible deposits, or they may act as barriers to ground-water flow, impeding the horizontal propagation of fluid-pressure changes and creating ground-water-level differences across the faults.

The potential for renewed subsidence in Santa Clara Valley, California, is a concern for the Santa Clara Valley Water District. One of the District's objectives in managing water resources is to limit ground-water extractions that would cause inelastic (irreversible) compaction of the valley's aquifer system. Seasonal and longer-term elevation changes were measured from successive satellite radar

InSAR imagery reveals seasonal and long-term land-surface-elevation changes influenced by ground-water levels and fault alignment in the Santa Clara Valley.

Long term uplift occurred between 1992 and 1997 due to recovering ground-water levels.

Seasonal, recoverable subsidence was measured between January and August 1997. Subsidence patterns during this period are similar to historical subsidence patterns (1934–1967).

(Ikehara and others, 1998)

passes during 1992 to 1997. The longer-term (~5 year) measurement indicates no change for most of the southwestern Santa Clara Valley and land-surface uplift of up to 1.4 inches in the northern and eastern parts of the valley. This uplift is correlated to the recovery of ground-water levels that has been occurring for several years as a result of reduced pumpage and increased recharge. In contrast, the seasonal (6–8 month) interferograms reveal a large region in San Jose undergoing seasonal elastic deformation related to ground-water-level fluctuations. The eastern extent of this deformation appears to be truncated by a Quaternary fault, the Silver Creek Fault, several miles west and roughly parallel to the tectonically active Hayward Fault. The InSAR maps are generally consistent with compaction measured in borehole extensometers.

MITIGATION MEASURES

When development of natural resources causes subsidence, governments sometimes exercise their power either to prohibit the re-

source development or to control it in ways that minimize damage. This may be done through regulation. With adequate monitoring programs and institutional mechanisms in place, optimal benefits may be achieved for both subsidence mitigation and resource development. The Panel on Land Subsidence (NRC, 1991) found that more research is needed in this area of optimal resource allocation and adaptive approaches to land- and water-use management.

In order to wisely and conjunctively manage our land and water resources we first need to define the relevant interacting processes. In the case of land subsidence and ground-water resources, this means understanding the hydrogeologic framework of the resource as well as the demands or stresses that we place on it. It also means identifying a desired state of the land and water resources—a set of goals and objectives that describe some desirable outcomes. These goals and objectives may require guidelines for decisionmaking (policy) to modify usage of the resources in order to attain the desired state. The selection and management of these policies can be based on measures of the condition of the hydrogeologic system.

General approaches to mitigation of subsidence will rarely apply to all types of subsidence.

Land-subsidence and water-management problems are linked

In a typical basin, ground water is in part a renewable resource; a certain amount may be extracted without seriously depleting the amount of water stored. This is the concept of the "safe yield" of a basin. In subsidence-prone alluvial aquifer systems, unless we wish to mine a significant volume of water in storage in the fine-grained sediments, the volume of water withdrawn cannot greatly exceed the natural and artificial replenishment. It may be necessary to maintain ground-water levels above critical thresholds in subsidence-prone areas within the basin in order to avoid incurring new or additional subsidence. Another important consideration is climatic variability, which affects the amount of water available for natural and artificial replenishment. This restricted concept of "safe yield" addresses only the volume of extracted water with respect to a dynamic equilibrium between the water recharging and discharging a basin. Beyond this, to conserve an aquifer system from a water-quality perspective, it may be necessary to maintain certain minimal flow-through rates.

Because aquifer systems have the capacity to store water, the amount of natural outflow from a basin may not be equal to the amount replenished in the same year. Thus the "optimal yield" of a ground-water basin is not necessarily a constant value. It may vary from year-to-year depending upon the state of the aquifer system and the availability of alternative local and imported supplies. The concept of optimal yield incorporates the dynamic nature of the ground-water basin and the adaptability of the management system (Bear, 1979). However, over the long term, the "annual safe yield" of a basin would be roughly equivalent to its average replenishment.

Adaptability has emerged as a conscious element of institutional design in basin-management programs (Blomquist, 1992). Managing basins according to optimal yield assumptions has allowed water

users to respond to changed conditions of water supply, including severe drought and relative abundance. Ground-water management plans typically address both demand and supply by adjusting the demands placed on the water-supply system through conservation and water-rationing programs, by adjusting the supply through conjunctive use of ground water and surface water, and by augmenting the supply through aquifer storage and recovery programs. Adaptable management alternatives contribute to the stability and sustainability of land and water resources in many basins.

In basins susceptible to detrimental effects related to the lowering of ground-water levels, such as the three types of subsidence presented in this Circular, land and water resources are linked. For alluvial ground-water basins subject to aquifer-system compaction, threshold values of aquifer-system stress define the boundary between nonpermanent (recoverable) and permanent (nonrecoverable) compaction and loss of land-surface elevation. For regions affected by the dissolution and collapse of soluble rocks, the threshold stress values are more ambiguous but nevertheless real and somewhat manageable. For oxidation of organic soils, the threshold for detrimental effects is very nearly defined by the position of the water table. In each case, management of the land-subsidence problem is inextricably linked to other facets of water-resource management.

Socioeconomic risks versus benefits

Ground-water basins have value not only as perennial sources of water supply, but also as reservoirs for cyclical recharge and discharge. While augmenting base water-supply needs met from a variety of water sources, ground-water basins may provide water at peak-demand periods to modulate the variability inherent in surface-water supplies. The conjunctive surface- and ground-water-management programs in some southern California basins make more efficient use of basin storage capacity than the fixed-yield management programs of other, nonconjunctively managed basins. Storing water underground in wet years for use in dry years, and encouraging water users to take more surface and imported water when it is plentiful and to pump more ground water when it is not, capitalizes on one of the strengths of the ground-water resource. Restricting pumping to the same amount each year regardless of basin conditions does not. In some cases, the most valuable use of ground-water basins is to lessen the immediate shock of short-term variability of water supply (Blomquist, 1992). In subsidence-prone basins, the need to maintain minimum water levels for subsidence control may place a significant constraint on conjunctive-use schemes.