THE ROLE OF SCIENCE

Land Subsidence in the United States

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

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

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

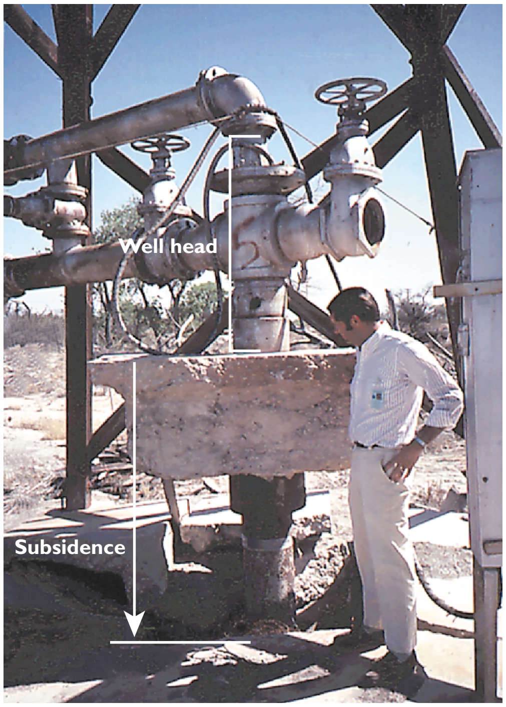
The occurrence of land subsidence is seldom as obvious as it is in the case of catastrophic sinkholes such as those in Winter Park, Florida, or at the Retsof Salt Mine in Genesee Valley, New York. Discovery of such catastrophic subsidence is difficult only when the localized collapse occurs in a remote 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.

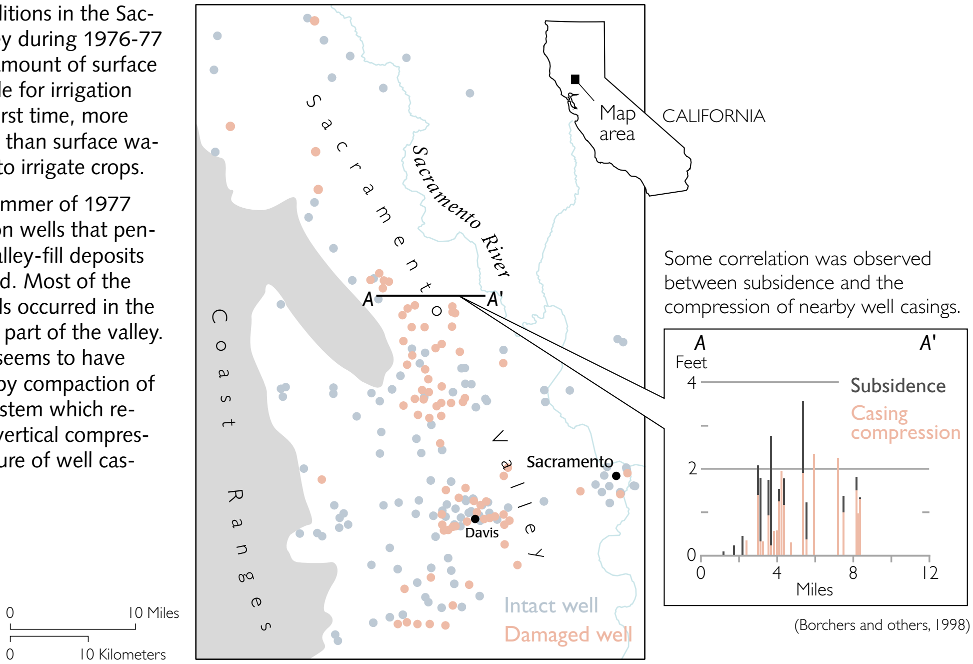


(Pictured is Terry Katzer)

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.

(Borchers and others, 1998)

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).

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

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.

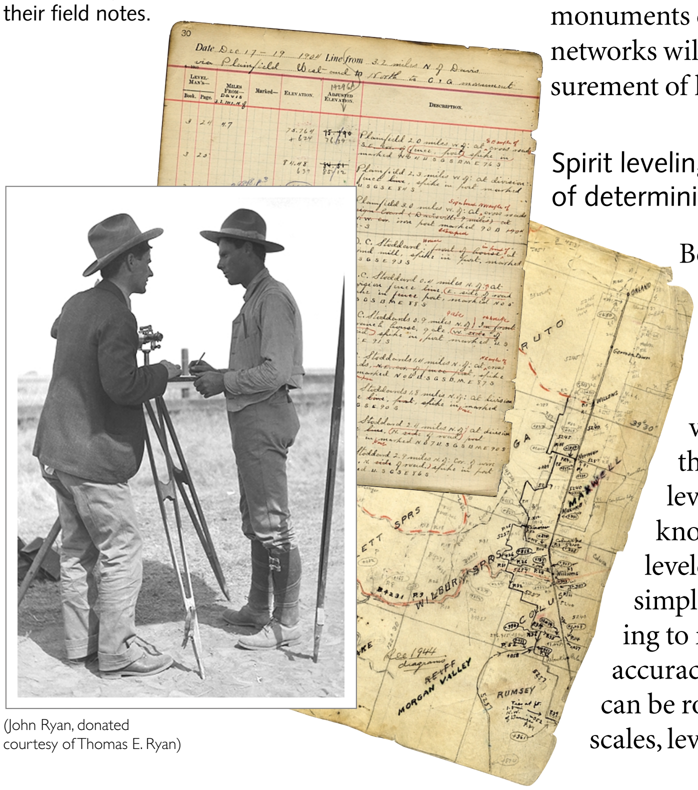
For more information on geodetic control, visit the National Geodetic Survey web site at **http://www.ngs.noaa.gov/faq.shtml**

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

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



30

Date Dec 17–19 1904 Line from 3.2 miles N of Davis
via Plainfield West and to North to C & G monument

Level Man's— Book.	Page.	Miles From— Davis 3.2 mi. N of	Marked—	Elevation.	1929 GA Adjusted Elevation.	Description.
3	24	4.7		75.764 +624	~~75.790~~ 76.39	Plainfield 2.0 miles W of: at SE angle of cross roads ~~S.E. cor. of~~ fence post, spike in marked ~~NO~~ U S G S B M E 76 S
3	25			84.48 639	~~84.51~~ 85.12	Plainfield 2.3 miles W of: at division fence ~~line~~, spike in post marked U S G S E 84 S

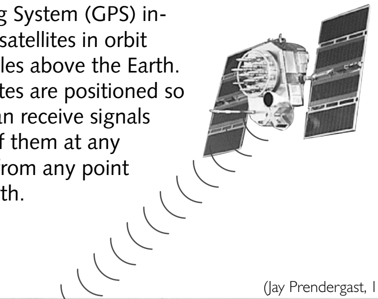
(John Ryan, donated courtesy of Thomas E. Ryan) the scale of the survey is small (on the order of 5 miles or less) and the desired spatial density is high, spirit leveling is still commonly used because it is accurate and relatively inexpensive. Large regional networks warrant use of the more efficient 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).

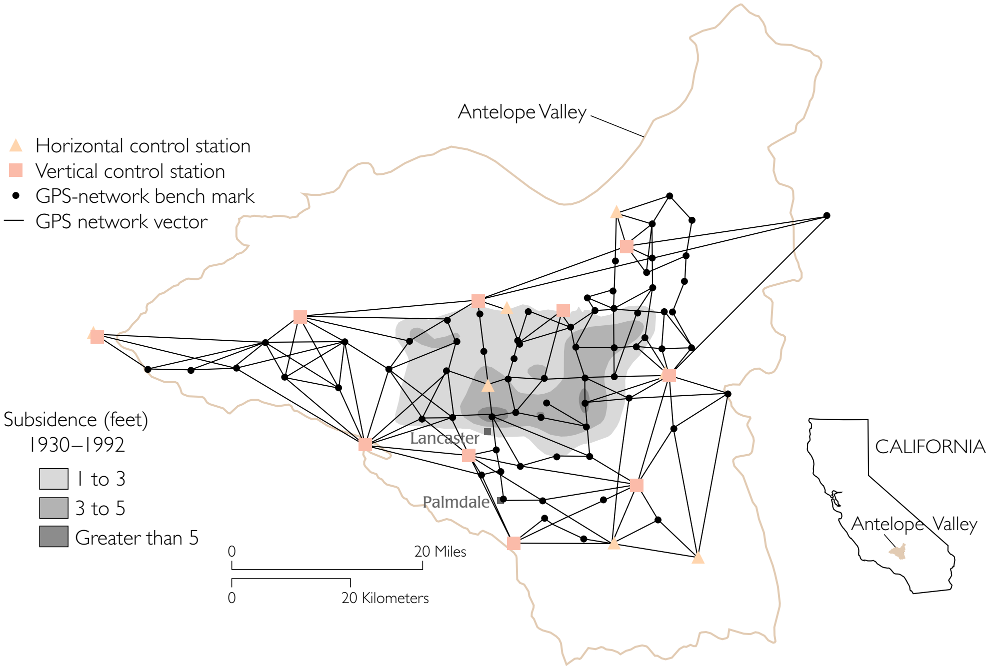
In land-subsidence and other crustal-motion surveys, the relative positions of two points can be determined when two GPS receivers, one at each observation point, receive signals simultaneously from the same set of 4 or more satellites. When the same points are reoccupied following some time interval, 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.



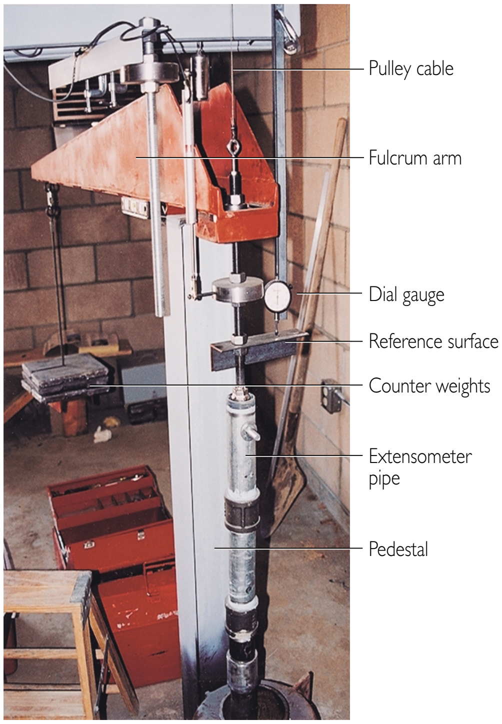
(Jay Prendergast, 1992)

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.



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 extensometer that measures compaction in a shallow aquifer near Lancaster,

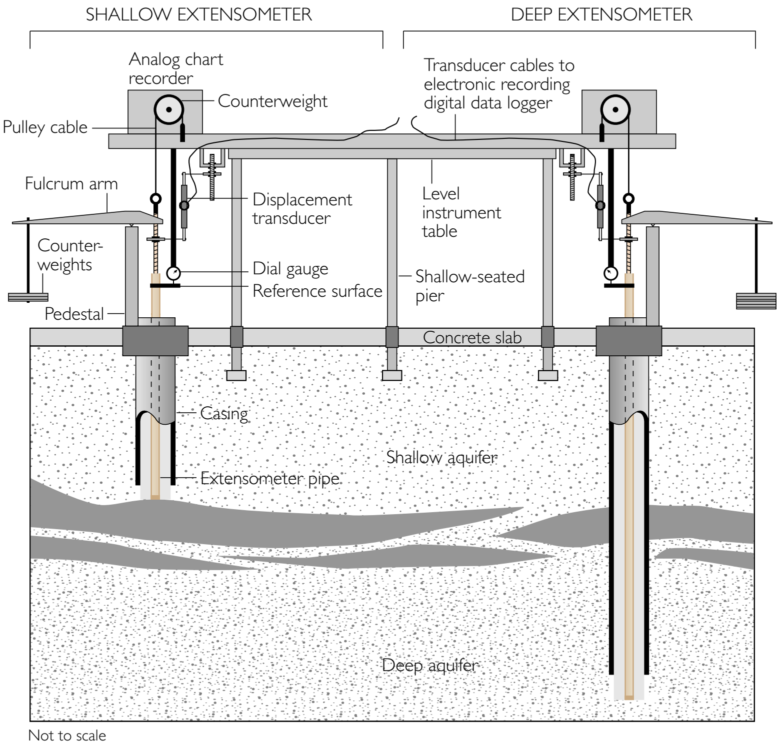
Desert, California in 1992 (Ikehara and Phillips, 1994). It was designed to determine the subsidence of previously leveled bench marks and enable precise measurement of points separated by tens of miles for future subsidence monitoring. Other large GPS-based geodetic networks for subsidence monitoring 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 surveying 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

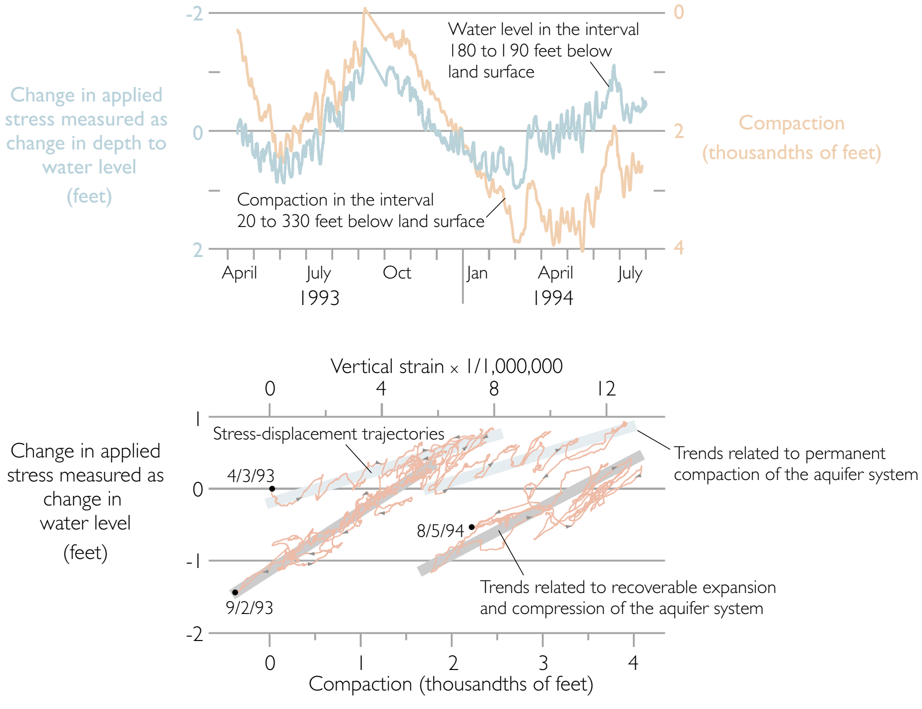
Borehole extensometers generate a continuous record of change in vertical distance between the land surface and a reference point or “subsurface bench mark” at the bottom of a deep borehole (Riley, 1986). In areas undergoing aquifer-system compaction, the extensometer is the most effective means of determining precise, continuous 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 extensometers in a single instrument are being used to measure aquifer-system compaction simultaneously in different depth intervals.

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

As the aquifer system compresses, the land surface subsides along with the extensometer table. The extensometer pipe anchored deeper in the aquifer system appears to rise relative to the table. This relative movement represents the amount of vertical displacement occurring in the aquifer system between the shallow-seated piers supporting the table and the bottom of the extensometer pipe.

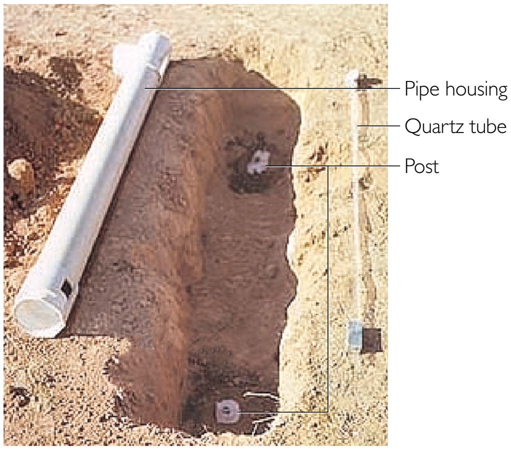


Measurements of water level and compaction from borehole extensometers form the basis of stress-strain analysis. These data are from the Hueco Basin, El Paso, Texas.



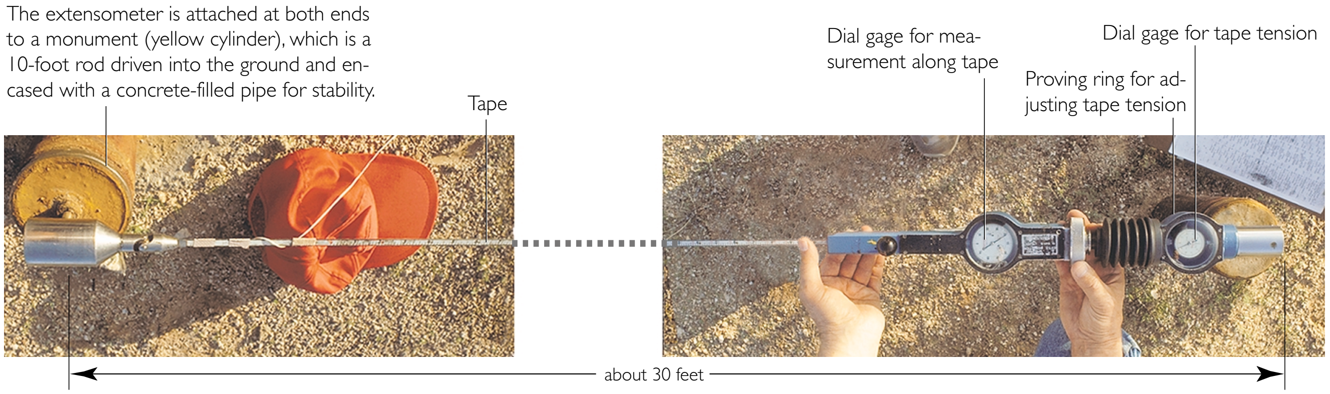
(Heywood, 1995)

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.



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



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.

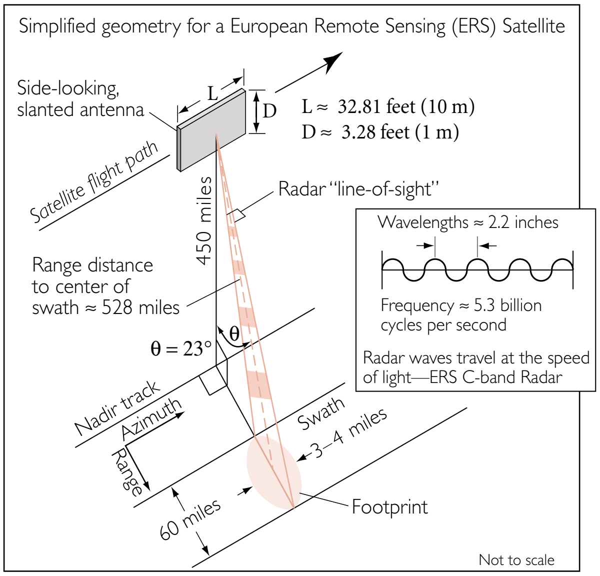
Radar interferometry is a new tool for measuring subsidence

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.



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.

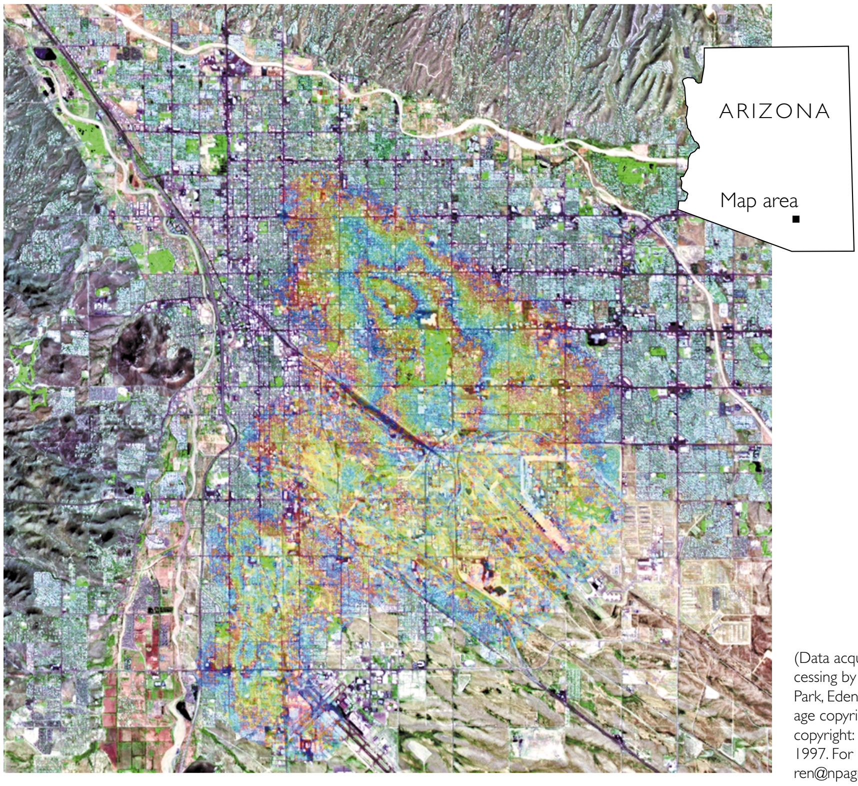
Interferograms are made by differencing successive SAR images taken from the same orbital position but at different times. Under favorable radiometric conditions 1/2-inch to 1/10-inch resolution is possible in the line-of-sight (range) of the radar.

*__RADAR__: **RA**dio **D**etection **A**nd **R**anging 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.

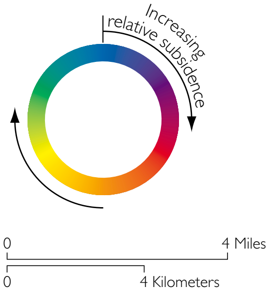
For landscapes with more or less stable radar reflectors (such as buildings or other engineered structures, or undisturbed rocks and ground surfaces) over a period of time, it is possible to make high-precision measurements of the change in the position of the reflectors by subtracting or "interfering" 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.

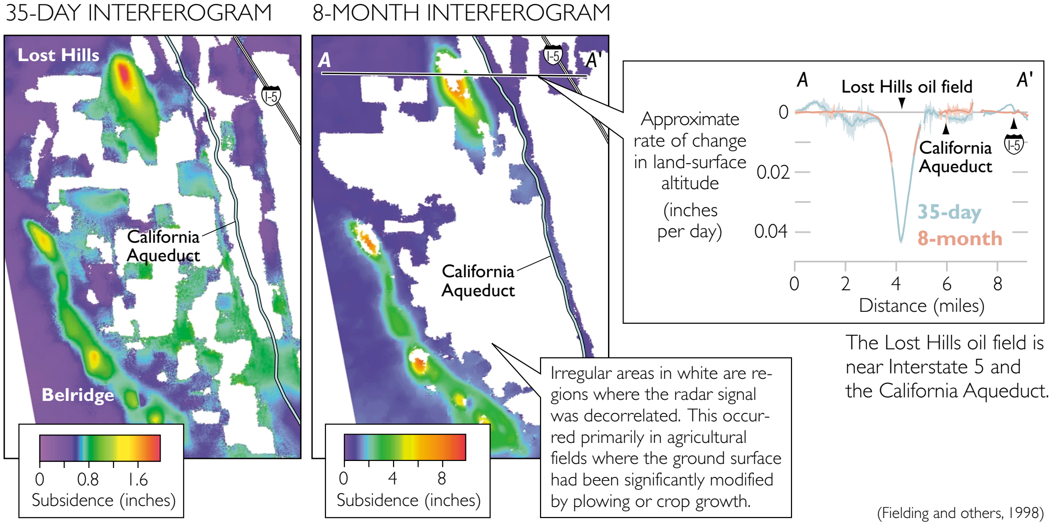


One color cycle represents about 1.1 inch of subsidence. More than two cycles can be seen on this Tucson image.



(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.



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.

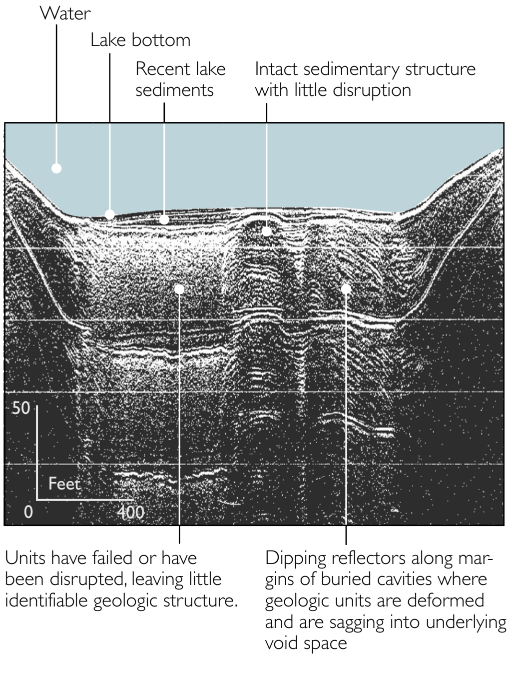
[3] A pixel on an InSAR displacement map is typically 40 to 80 meters square on the ground.

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.



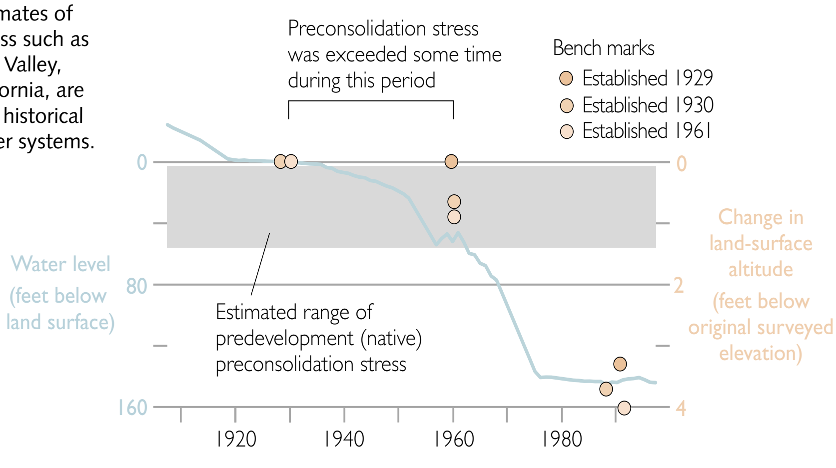
An acoustic profile taken across a sinkhole lake in west-central Florida shows how high-resolution seismic-reflection techniques can image geologic characteristics associated with subsidence.

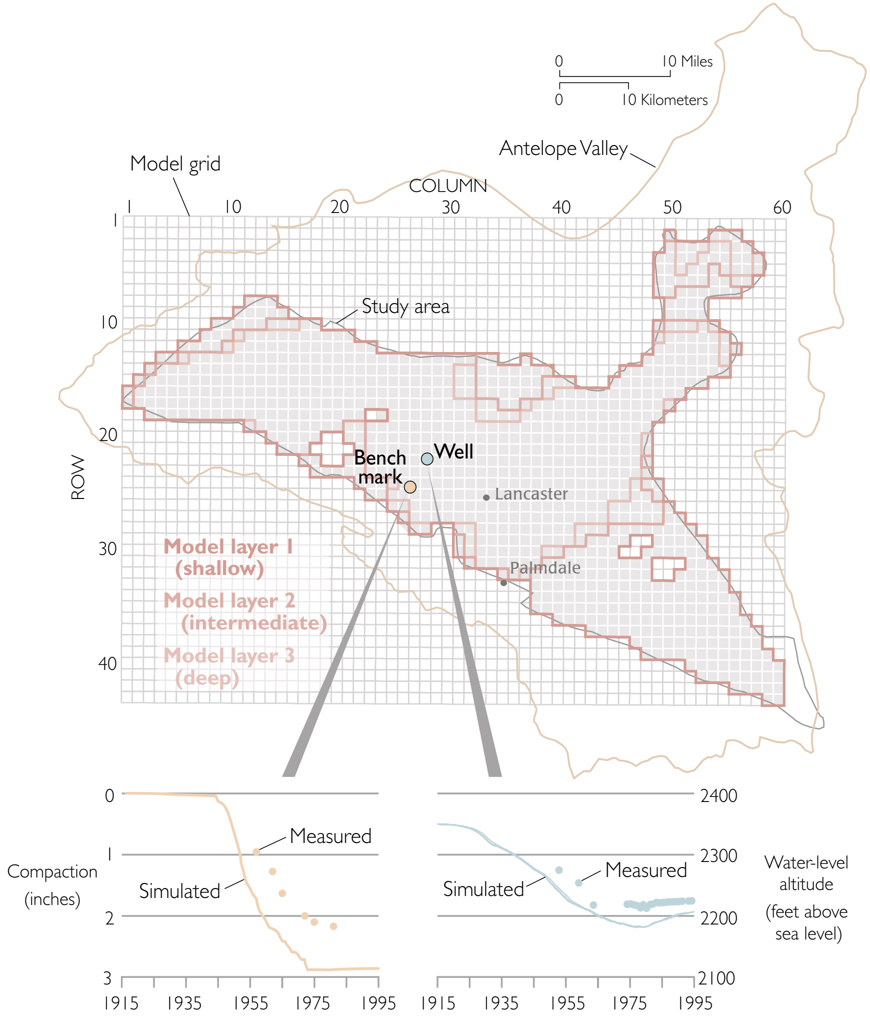
(Tihansky and others, 1996)

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

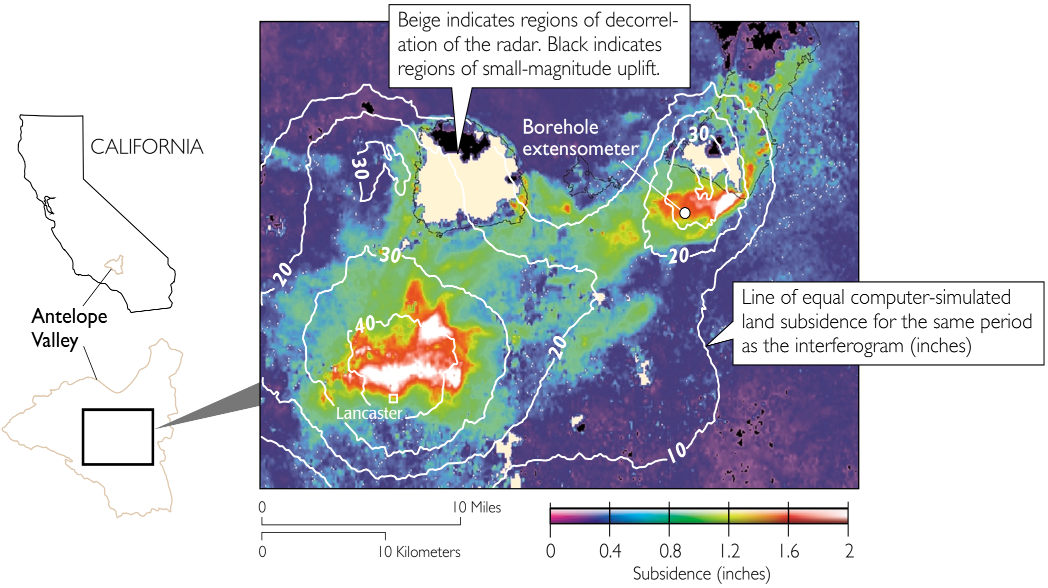
Since the advent of high-speed digital computers, scientists have had the ability to numerically simulate the flow of ground water and associated aquifer-system compaction in multiple dimensions. In actual practice, ground-water flow may be simulated in one, two, or three dimensions, but compaction is 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 important 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

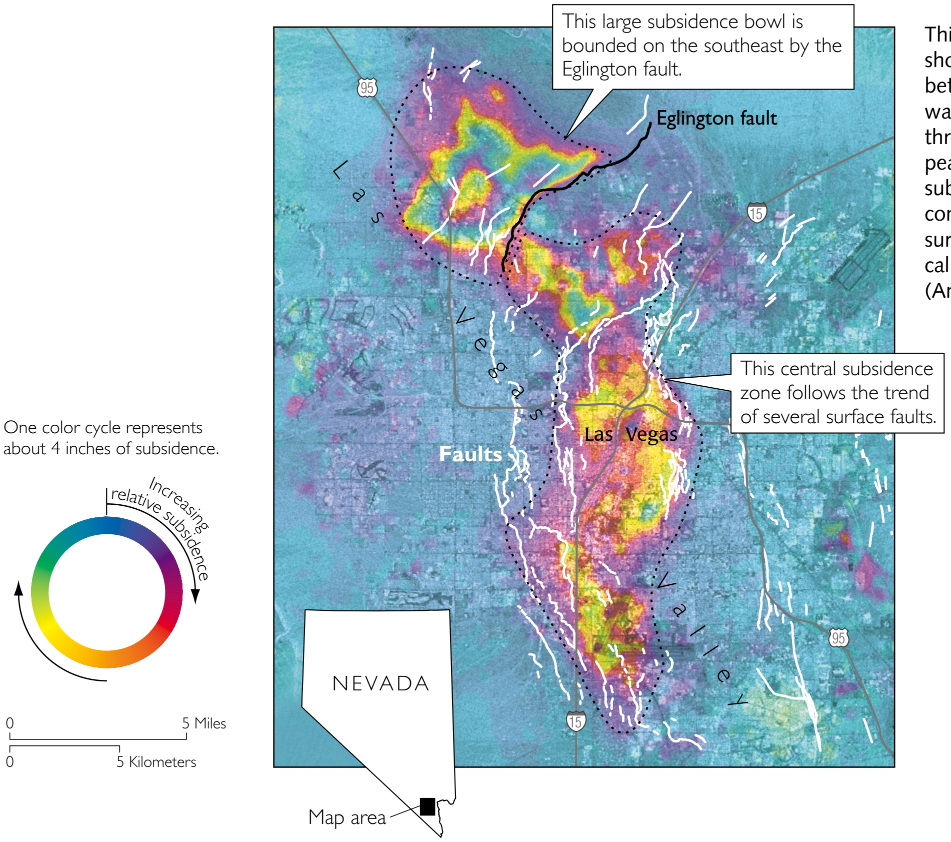
In the Antelope Valley, Mojave Desert, California, a radar interferogram for the period October 20, 1993 to December 22, 1995 revealed up to 2 inches of subsidence in areas previously affected by as much as 6 feet of subsidence since 1930 (Galloway and others, 1998). The regions of maximum subsidence 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.



Beige indicates regions of decorrelation of the radar. Black indicates regions of small-magnitude uplift.

Line of equal computer-simulated land subsidence for the same period as the interferogram (inches)



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

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

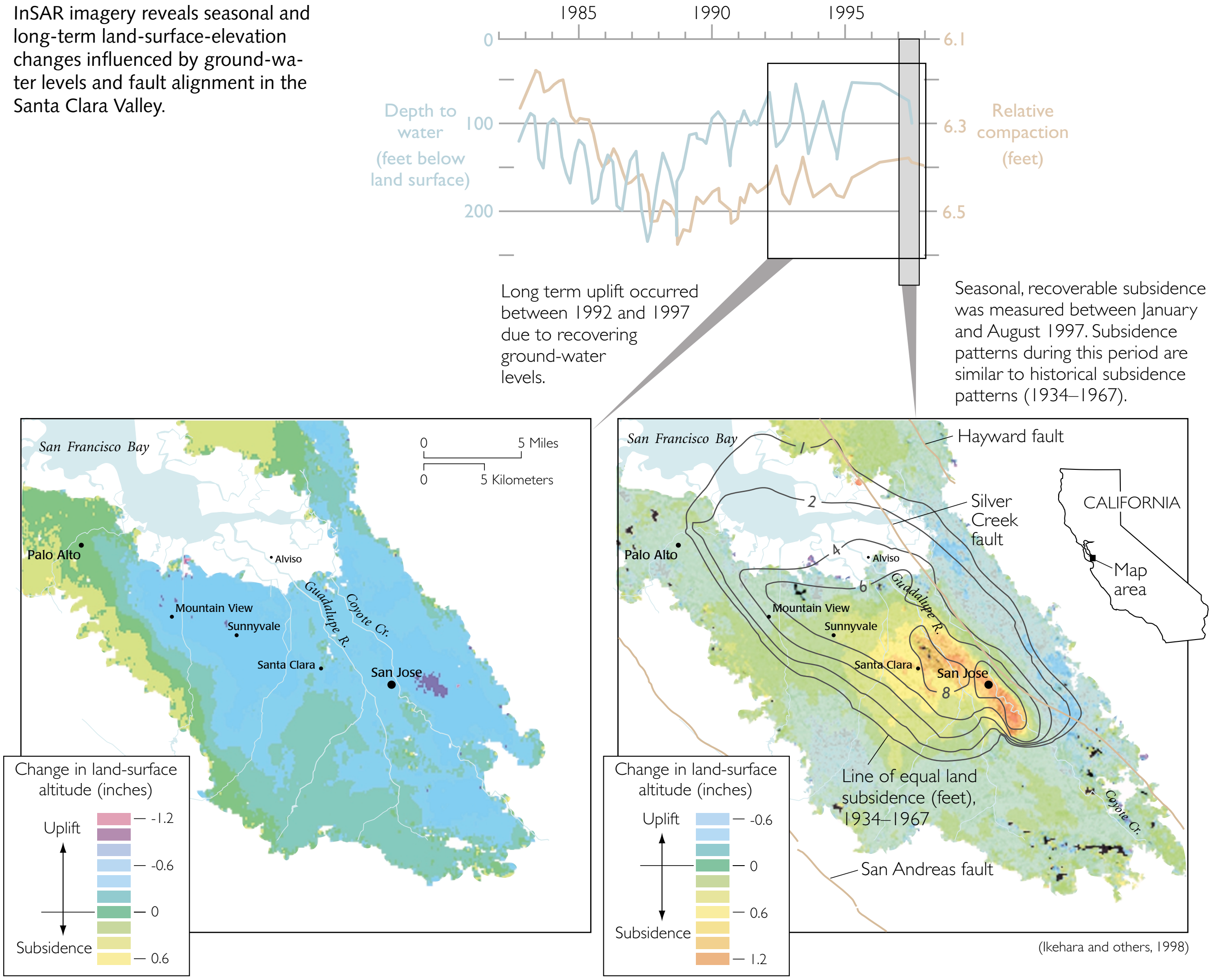
One color cycle represents about 4 inches of subsidence.

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).

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.



(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 resource 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.

GLOSSARY

Land Subsidence in the United States

These definitions are based on the American Geological Institute's **Glossary of Geology** (4th edition) and **Glossary of Hydrology**, and USGS Water Supply Paper 2025, "Glossary of selected terms useful in studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawal" (Poland, and others, 1971).

Aquifer	A saturated, permeable, geologic unit that can transmit significant quantities of ground water under ordinary hydraulic gradients and is permeable enough to yield economic quantities of water to wells.
Aquifer, Artesian	See *Aquifer, Confined, and Artesian.*
Aquifer, Confined	An artesian aquifer that is confined between two aquitards.
Aquifer,Unconfined	A water-table aquifer in which the water table forms the upper boundary.
Aquifer System	A heterogeneous body of interbedded permeable and poorly permeable geologic units that function as a water-yielding hydraulic unit at a regional scale. The aquifer system may comprise one or more aquifers within which aquitards are interspersed. Confining units may separate the aquifers and impede the vertical exchange of ground water between aquifers within the aquifer system.
Aquitard	A saturated, but poorly permeable, geologic unit that impedes ground-water movement and does not yield water freely to wells, but which may transmit appreciable water to and from adjacent aquifers and, where sufficiently thick, may constitute an important ground-water storage unit. Areally extensive aquitards may function regionally as confining units within aquifer systems. See also *Confining Unit*.
Artesian	An adjective referring to confined aquifers. Sometimes the term artesian is used to denote a portion of a confined aquifer where the altitudes of the potentiometric surface are above land surface (flowing wells and artesian wells are synonymous in this usage). But more generally the term indicates that the altitudes of the potentiometric surface are above the altitude of the base of the confining unit (artesian wells and flowing wells are not synonymous in this case). See *Aquifer, Confined*.
Blue hole	A subsurface void, usually a solution sinkhole, developed in carbonate rocks that are open to the Earth's surface and contains tidally influenced waters of fresh, marine, or mixed chemistry.
Cave	A natural underground open space or series of open spaces and passages large enough for a person to enter, generally with a connection to the surface; often formed by solution of limestone.

Cavern	A cave, with the implication of a large size.
Cenote	Steep-walled natural well that extends below the water table; generally caused by collapse of a cave roof; term reserved for features found in the Yucatan Peninsula of Mexico.
Confining Unit	A saturated, relatively low-permeability geologic unit that is areally extensive and serves to confine an adjacent artesian aquifer or aquifers. Leaky confining units may transmit appreciable water to and from adjacent aquifers. See also *Aquitard*.
Compaction	In this Circular, compaction is used in its geologic sense and refers to the inelastic compression of the aquifer system. Compaction of the aquifer system reflects the rearrangement of the mineral grain pore structure and largely nonrecoverable reduction of the porosity under stresses greater than the preconsolidation stress. Compaction, as used here, is synonymous with the term "virgin consolidation" used by soils engineers. The term refers to both the process and the measured change in thickness. As a practical matter, a very small amount (1 to 5 percent) of the compaction is recoverable as a slight elastic rebound of the compacted material if stresses are reduced.
Compaction, Residual	Compaction that would ultimately occur if a given increase in applied stress were maintained until steady-state pore pressures were achieved. Residual compaction may also be defined as the difference between (1) the amount of compaction that will occur ultimately for a given increase in applied stress, and (2) that which has occurred at a specified time.
Compression	In this Circular, compression refers to the decrease in thickness of sediments, as a result of increase in vertical compressive stress. Compression may be elastic (fully recoverable) or inelastic (nonrecoverable).
Consolidation	In soil mechanics, consolidation is the adjustment of a saturated soil in response to increased load, involving the squeezing of water from the pores and a decrease in void ratio or porosity of the soil. In this Circular, the geologic term "compaction" is used in preference to consolidation.
Datum	See *Geodetic Datum.*
Ellipsoid, Earth	A mathematically determined three-dimensional surface obtained by rotating an ellipse about its semi-minor axis. In the case of the Earth, the ellipsoid is the modeled shape of its surface, which is relatively flattened in the polar axis.
Ellipsoid, Height	The distance of a point above the ellipsoid measured perpendicular to the surface of the ellipsoid.
Exfoliation	The process by which concentric scales, plates, or shells of rock, from less than a centimeter to several meters in thickness, are stripped from the bare surface of a large rock mass. See *spall.*
Geodetic Datum	A set of constants specifying the coordinate system used for geodetic control, for example, for calculating the coordinates of points on the Earth.

Geoid, Earth	The sea-level equipotential surface or figure of the Earth. If the Earth were completely covered by a shallow sea, the surface of this sea would conform to the geoid shaped by the hydrodynamic equilibrium of the water subject to gravitational and rotational forces. Mountains and valleys are departures from this reference geoid.
Head, Hydraulic	A measure of the potential for fluid flow. The height of the free surface of a body of water above a given subsurface point.
Hydraulic Conductivity	A measure of the medium's capacity to transmit a particular fluid. The volume of water at the existing kinematic viscosity that will move in a porous medium in unit time under a unit hydraulic gradient through a unit area. In contrast to permeability, it is a function of the properties of the liquid as well as the porous medium.
Hydrocompaction	The process of volume decrease and density increase that occurs when certain moisture-deficient deposits compact as they are wetted for the first time since burial. The vertical downward movement of the land surface that results from this process has also been termed "shallow subsidence" and "near-surface subsidence."
Karst	A type of topography that is formed on limestone, dolomite, gypsum and other rocks, primarily by dissolution, and that is characterized by sinkholes, caves, and subterranean drainage.
Karstification	Action by water, mainly chemical but also mechanical, that produces features of a karst topography.
Karst, Mantled	A terrane of karst features, usually subdued, and covered by soil or a thin alluvium.
Load	We refer to *Load* as synonymous with *Stress*.
Overdraft	Any withdrawal of ground water in excess of the *Safe Yield*.
Paleokarst	A karstified area that has been buried by later deposition of sediments.
Permeability	The capacity of a porous rock, sediment, or soil for transmitting a fluid. Unlike hydraulic conductivity, it is a function only of the medium.
pH	A measure of the acid/base property of a material sample. The negative logarithm of the hydrogen ion concentration; pH 7 is neutral with respect to distilled, deionized water; pH less than 7 is more acidic; pH greater than 7 is more basic.
Piezometric Surface	See *Potentiometric Surface.*
Plutonic	A loosely defined term with a number of current usages. We use it to describe igneous rock bodies that crystallized at great depth or, more generally, any intrusive igneous rock.
Porosity	The percentage of the soil or rock volume that is occupied by pore space, void of material. The porosity is defined by the ratio of void space to the total volume of a specimen.
Potentiometric Surface	An imaginary surface representing the total head of ground water and defined by the level to which the water will rise in a tightly cased well. See *Head, Hydraulic*.

Recharge	The process involved in addition of water to the saturated zone, naturally by precipitation or runoff, or artificially by spreading or injection.
Sinkhole	A depression in a karst area. At land surface its shape is generally circular and its size measured in meters to tens of meters; underground it is commonly funnel-shaped and associated with subterranean drainage.
Safe Yield	See *Yield, Safe.*
Specific Storage	The volume of water that an aquifer system releases or takes into storage per unit volume per unit change in head. The specific storage is equivalent to the *Storage Coefficient* divided by the thickness of the aquifer system.
Spall	A chip or fragment removed from a rock surface by weathering; especially by the process of exfoliation. See *exfoliation.*
Spring	Any natural discharge of water from rock or soil onto the land surface or into a surface-water body.
Storage	The capacity of an aquifer, aquitard, or aquifer system to release or accept water into ground-water storage, per unit change in hydraulic head. See *Storage Coefficient* and *Specific Storage.*
Storage Coefficient	The volume of water that an aquifer system releases or takes into storage per unit surface area per unit change in head.
Strain	Relative change in the volume, area or length of a body as a result of *stress*. The change is expressed in terms of the amount of displacement measured in the body divided by its original volume, area, or length, and referred to as either a volume strain, areal strain, or one-dimensional strain, respectively. The unit measure of strain is dimensionless, as its value represents the fractional change from the former size.
Stress	In a solid body, the force (per unit area) acting on any surface within it; also refers to the applied force (per unit area) that creates the internal force. Stress is variously expressed in units of pressure, such as pounds per square inch, kilograms per square meter, or Pascals.
Stress, Applied	The downward stress imposed on a specified horizontal plane within an aquifer system. At any given level in the aquifer system, the applied stress is the force or weight (per unit area) of sediments and moisture above the water table, plus the submerged weight (per unit area), accounting for buoyancy of the saturated sediments overlying the specified plane at that level, plus or minus the net seepage stress generated by flow (upward or downward component) through the specified plane in the aquifer system.
Stress, Effective	Stress (pressure) that is borne by and transmitted through the grain-to-grain contacts of a deposit, and thus affects its porosity and other physical properties. In one-dimensional compression, effective stress is the average grain-to-grain load per unit area in a plane normal to the applied stress. At any given depth, the effective

	stress is the weight (per unit area) of sediments and moisture above the water table, plus the submerged weight (per unit area) of sediments between the water table and the specified depth, plus or minus the seepage stress (hydrodynamic drag) produced by downward or upward components, respectively, of water movement through the saturated sediments above the specified depth. Effective stress may also be defined as the difference between the geostatic stress and fluid pressure at a given depth in a saturated deposit, and represents that portion of the applied stress which becomes effective as intergranular stress.
Stress, Geostatic (Lithostatic)	The total weight (per unit area) of sediments and water above some plane of reference. Geostatic stress normal to any horizontal plane of reference in a saturated deposit may also be defined as the sum of the effective stress and the fluid pressure at that depth.
Stress, Preconsolidation	The maximum antecedent effective stress to which a deposit has been subjected and which it can withstand without undergoing additional permanent deformation. Stress changes in the range less than the preconsolidation stress produce elastic deformations of small magnitude. In fine-grained materials, stress increases beyond the preconsolidation stress produce much larger deformations that are principally inelastic (nonrecoverable). Synonymous with "virgin stress."
Stress, Seepage	Force (per unit area) transferred from the water to the medium by viscous friction when water flows through a porous medium. The force transferred to the medium is equal to the loss of hydraulic head and is termed the seepage force exerted in the direction of flow.
Subsidence	Sinking or settlement of the land surface, due to any of several processes. As commonly used, the term relates to the vertical downward movement of natural surfaces although small-scale horizontal components may be present. The term does not include landslides, which have large-scale horizontal displacements, or settlements of artificial fills.
Subsidence, Near-Surface	See *Hydrocompaction.*
Subsidence, Shallow	See *Hydrocompaction.*
Transmissivity	The rate at which water at the prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient. See also *Hydraulic Conductivity*.
Vug	A small cavity or chamber in rock that may be lined with crystals.
Water Table	The surface of a body of unconfined ground water at which the pressure is equal to atmospheric pressure.
Yield, Operational	See *Yield, Optimal.*
Yield, Optimal	An optimal amount of ground water, by virtue of its use, that should be withdrawn from an aquifer system or ground-water basin each year. It is a dynamic quantity that must be determined from a set of alternative ground-water management decisions subject to goals, objectives, and constraints of the management plan.

Yield, Perennial	The amount of usable water from an aquifer that can be economically consumed each year for an indefinite period of time. It is a specified amount that is commonly specified equal to the mean annual recharge to the aquifer system, which thereby limits the amount of ground water that can be pumped for beneficial use.
Yield, Safe	The amount of ground water that can be safely withdrawn from a ground-water basin annually, without producing an undesirable result. Undesirable results include but are not limited to depletion of ground-water storage, the intrusion of water of undesirable quality, the contraventions of existing water rights, the deterioration of the economic advantages of pumping (such as excessively lowered water levels and the attendant increased pumping lifts and associated energy costs), excessive depletion of streamflow by induced infiltration, and land subsidence.

REFERENCES

Land Subsidence in the United States

Introduction

Ege, J.R., 1984, Mechanisms of surface subsidence resulting from solution extraction of salt, *in* Holzer, T.L., ed., Man-induced land subsidence: Geological Society of America Reviews in Engineering Geology, v. 6, p. 203–221.

Lucas, R.E., 1982, Organic soils (Histosols)—Formation, distribution, physical and chemical properties and management for crop production: Michigan State University Farm Science Research Report 435, 77 p.

National Research Council, 1991, Mitigating losses from land subsidence in the United States: Washington, D. C., National Academy Press, 58 p.

Stephens, J.C., Allen, L.H., Jr., and Chen, Ellen, 1984, Organic soil subsidence, *in* Holzer, T.L., ed., Man-induced land subsidence: Geological Society of America Reviews in Engineering Geology, v. 6, p. 107–122.

White, W.B., Culver, D.C., Herman, J.S., Kane, T.C., and Mylroie, J.E., 1995, Karst lands: American Scientist, v. 83, p. 450–459.

PART I—Mining Ground Water

INTRODUCTION

Clawges, R. M., and Price, C. V., 1999, Digital data sets describing principal aquifers, surficial geology, and ground-water regions of the conterminous United States: U.S. Geological Survey Open-File Report 99-77 [accessed Sept. 17, 1999 at URL http://water.usgs.gov/pubs/ofr/ofr99-77].Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N. J. Prentice-Hall, 604 p.

Green, J.H., 1964, Compaction of the aquifer system and land subsidence in the Santa Clara Valley, California: U.S. Geological Survey Water-Supply Paper 1779-T, 11 p.

Helm, D.C., 1975, One-dimensional simulation of aquifer system compaction near Pixley, Calif., part 1. Constant parameters: Water Resources Research, v. 11, p. 465–478.

Heywood, C.E., 1997, Piezometric-extensometric estimations of specific storage in the Albuquerque Basin, New Mexico: *in* Prince, K.R., and Leake, S.A., eds., U.S. Geological Survey Open-File Report 97–47, p. 21–26.

Holzer, T.L., 1998, History of the aquitard-drainage model in land subsidence case studies and current research, *in* Borchers, J.W., ed., Land subsidence case studies and current research: Proceedings of the Dr. Joseph F. Poland symposium on land subsidence, Association of Engineering Geologists Special Publication No. 8, p. 7–12.

Ireland, R.L., Poland, J.F., and Riley, F.S., 1984, Land subsidence in the San Joaquin Valley, California as of 1980: U.S. Geological Survey Professional Paper 437-I, 93 p.

Miller, R.E., 1961, Compaction of an aquifer system computed from consolidation tests and decline in artesian head: U.S. Geological Survey Professional Paper 424-B, p. B54–B58.

Poland, J.F., 1960, Land subsidence in the San Joaquin Valley and its effect on estimates of ground-water resources: International Association of Scientific Hydrology, IASH Publication 52, p. 324–335.

Poland, J.F., and Green, J.H., 1962, Subsidence in the Santa Clara Valley, California—a progress report: U.S. Geological Survey Water-Supply Paper 1619-C, 16 p.

Poland, J.F., Lofgren, B.E., Ireland, R.L., and Pugh, R.G., 1975, Land subsidence in the San Joaquin Valley, California as of 1972: U.S. Geological Survey Professional Paper 437-H, 78 p.

Poland, J.F., ed., 1984, Guidebook to studies of land subsidence due to ground-water withdrawal: United Nations Educational, Scientific and Cultural Organization, Paris, Studies and reports in hydrology 40, 305 p.

Poland, J.F., and Ireland, R.L., 1988, Land subsidence in the Santa Clara Valley, California, as of 1982: U.S. Geological Survey Professional Paper 497-F, 61 p.

Riley, F.S., 1969, Analysis of borehole extensometer data from central California: International Association of Scientific Hydrology Publication 89, p. 423–431.

Riley, F.S., 1998, Mechanics of aquifer systems—The scientific legacy of Joseph F. Poland, in Borchers, J.W., ed., Land subsidence case studies and current research: Proceedings of the Dr. Joseph F. Poland symposium on land subsidence, Association of Engineering Geologists Special Publication No. 8, p. 13–27.

Terzaghi, K., 1925, Principles of soil mechanics, IV—Settlement and consolidation of clay: Engineering News-Record, 95(3), p. 874–878.

Tolman, C.F., and Poland, J.F., 1940, Ground-water infiltration, and ground-surface recession in Santa Clara Valley, Santa Clara County, California: Transactions American Geophysical Union, v. 21, p. 23–34.

SANTA CLARA VALLEY, CALIFORNIA

California History Center, 1981, Water in the Santa Clara Valley—A history: De Anza College California History Center Local History Studies v. 27, 155 p.

Fowler, L.C., 1981, Economic consequences of land surface subsidence: Journal of the Irrigation and Drainage Division, American Society of Civil Engineers, v. 107, p. 151–159.

Poland, J.F., 1977, Land subsidence stopped by artesian head recovery, Santa Clara Valley, California: International Association of Hydrological Sciences Publication 121, p. 124–132.

Poland, J.F., and Ireland, R.L., 1988 , Land subsidence in the Santa Clara Valley, California, as of 1982: U.S. Geological Survey Professional Paper 497-F, 61 p.

Reichard, E.G., and Bredehoeft, J.D., 1984, An engineering economic analysis of a program for artificial groundwater recharge: Water Resources Bulletin, v. 20, p. 929–939.

Tolman, C.F., and Poland, J.F. 1940, Ground-water infiltration, and ground-surface recession in Santa Clara Valley, Santa Clara County, California: Transactions American Geophysical Union, v. 21, p. 23–34.

SAN JOAQUIN VALLEY, CALIFORNIA

Cone, Tracy, 1997, The vanishing valley: San Jose Mercury News West Magazine, June 29, p. 9–15.

EDAW-ESA, 1978, Environmental and economic effects of subsidence: Lawrence Berkeley Laboratory Geothermal Subsidence Research Program Final Report—Category IV, Project 1, [variously paged].

Ingerson, I. M., 1941, The hydrology of the southern San Joaquin Valley, California, and its relation to imported water supplies: Transactions American Geophysical Union, v. 22, p. 20–45.

Ireland, R.L., Poland, J.F., and Riley, F.S., 1984, Land subsidence in the San Joaquin Valley, California as of 1980: U.S. Geological Survey Professional Paper 437-I, 93 p.

Manning, J.C., 1967, Report on the ground-water hydrology in the southern San Joaquin Valley: American Water Works Association Journal, v. 59, p. 1,513–1,526.

Mendenhall, W.C., Dole, R.B., and Stabler, Herman, 1916, Ground water in San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 398, 310 p.

Nady, Paul, and Larragueta, L.L., 1983, Development of irrigation in the Central Valley of California: U.S. Geological Survey Hydrologic Investigations Atlas HA-649, scale 1:500,000, 2 sheets.

Poland, J.F., Lofgren, B.E., Ireland, R.L., and Pugh, R.G., 1975, Land subsidence in the San Joaquin Valley, California, as of 1972: U.S. Geological Survey Professional Paper 437-H, 78 p.

Swanson, A.A., 1998, Land subsidence in the San Joaquin Valley, updated to 1995, *in* Borchers, J.W., ed., Land subsidence case studies and current research: Proceedings of the Dr. Joseph F. Poland symposium on land subsidence, Association of Engineering Geologists Special Publication No. 8, p. 75–79.

Williamson, A.K., Prudic, D.E., and Swain, L.A., 1989, Ground-water flow in the Central Valley, California: U.S. Geological Survey Professional Paper 1401-D, 127 p.

HOUSTON-GALVESTON, TEXAS

Gabrysch, R.K., 1983, The impact of land-surface subsidence, *in* Impact of Science on Society, Managing our fresh-water resources: United Nations Educational, Scientific and Cultural Organization No. 1, p. 117–123.

Galveston Bay National Estuary Program, 1995, The Galveston Bay plan—The comprehensive land management plan for the Galveston Bay ecosystem, Oct. 18, 1994: Galveston Bay National Estuary Program Publication GBNEP-49, 457 p.

Holzer, T.L., 1984, Ground failure induced by ground water withdrawal from unconsolidated sediment, *in* Holzer, T.L., ed., Man-induced land subsidence: Geological Society of America Reviews in Economic Geology, v. 6, p. 67–105.

Holzer, T.L., and Gabrysch, R.K., 1987, Effect of water-level recoveries on fault creep, Houston, Texas: Ground Water, v. 25, p. 392–397.

Holzschuh, J.C., 1991, Land subsidence in Houston, Texas U.S.A.: Field-trip guidebook for the fourth international symposium on land subsidence, May 12–17, 1991, Houston, Tex., 22 p.

Kasmarek, M.C., Coplin, L.S., and Santos, H.X., 1997, Water-level altitudes 1997, water-level changes 1977–97 and 1996–97, and compaction 1973–96 in the Chicot and Evangeline Aquifers, Houston-Galveston Region, Texas: U.S. Geological Survey Open-File Report 97-181, 8 sheets, scale 1:100,000.

McGowen, J.M., Garner, L.E., and Wilkinson, B.M., 1977, The Gulf shoreline of Texas—processes, characteristics, and factors in use: University of Texas, Bureau of Economic Geology, Geological Circular 75-6, 43 p.

Jones, L.L., 1976, External costs of surface subsidence— Upper Galveston Bay, Texas: International Symposium on Land Subsidence, 2nd, Anaheim, Calif., December 1976, [Proceedings] International Association of Hydrological Sciences Publication 121, p. 617–627.

Paine, J.G., 1993, Subsidence of the Texas coast—Inferences from historical and late Pleistocene sea levels: Tectonophysics, v. 222, p. 445–458.

Paine, J.G., and Morton, R.A., 1986, Historical shoreline changes in Trinity, Galveston, West, and East Bays, Texas Gulf Coast: University of Texas Bureau of Economic Geology Circular 86-3, 58 p.

Pratt, W.E., and Johnson, D.W., 1926, Local subsidence of the Goose Creek oil field: Journal of Geology, v. 34, p. 577–590.

Titus, J.G., and Narayanan, V.K., 1995, The probability of sea level rise: U.S. Environmental Protection Agency, EPA 230-R-95-008.

White, W.A., Tremblay, T.A., Wermund, E.G., Jr., and Handley, L.R., 1993, Trends and status of wetland and aquatic habitats in the Galveston Bay system, Texas: Galveston Bay National Estuary Program Publication GBNEP-31, 225 p.

LAS VEGAS, NEVADA

Acevedo, William, Gaydos, Leonard, Tilley, Janet, Mladinich, Carol, Buchanan, Janis, Blauer, Steve, Kruger, Kelley, and Schubert, Jamie, 1997, Urban land use change in the Las Vegas Valley: U.S. Geological Survey, accessed July 27, 1999, http://geochange.er.usgs.gov/sw/changes/anthropogenic/population/las_vegas.

Bell, J.W., 1981a, Subsidence in Las Vegas Valley: Nevada Bureau of Mines and Geology Bulletin 95, 83 p., 1 plate, scale 1:62,500.

Bell, J.W., 1981b, Results of leveling across fault scarps in Las Vegas Valley, Nevada, April 1978–June 1981: Nevada Bureau of Mines and Geology Open-File Report 81-5, 7 p.

Bell, J.W., and Helm, D.C., 1998, Ground cracks on Quaternary faults in Nevada—Hydraulic and tectonic, in Borchers, J.W., ed., Land subsidence case studies and current research: Proceedings of the Dr. Joseph F. Poland symposium on land subsidence, Association of Engineering Geologists Special Publication No. 8, p. 165–173.

Bell, J.W., and Price, J.G., 1991, Subsidence in Las Vegas Valley, 1980–91—Final project report: Nevada Bureau of Mines and Geology, Open-File Report 93-4, 10 sect., 9 plates, scale 1:62,500.

Bernholtz, A., Brothers, K., and Katzer, T., 1994, Artificial ground-water recharge in Las Vegas Valley, Clark County, Nevada— Storing today, treating tomorrow?: International Symposium on Artificial Recharge of Ground Water, 2nd, Orlando, Fla., July 1994, [Proceedings], p. 548–557.

Burbey, T.J., 1995, Pumpage and water-level change in the principal aquifer of Las Vegas Valley, 1980–90—Nevada Division of Water Resources Information Report 34, 224 p.

Carpenter, Everett, 1915, Ground water in southeastern Nevada: U.S. Geological Survey Water-Supply Paper 365, 86 p.

Coache, Robert, 1996, Las Vegas Valley water usage report, Clark County, Nevada, 1996: Nevada Division of Water Resources Report, [50+] p.

Dettinger, M.D., 1989, Reconnaissance estimates of natural recharge to desert basins in Nevada, U.S.A., by using chloride balance calculations: Journal of Hydrology, v. 106, p. 55–78.

Domenico, P.A., Stephenson, D.A., and Maxey, G.B., 1964, Ground water in Las Vegas Valley: Nevada Department of Conservation and Natural Resources Division of Water Resources Bulletin 29, 53 p.

Hafen, L.R., and Hafen, A.W., 1954, Old Spanish Trail, Santa Fe to Los Angeles—With extracts from contemporary records and including diaries of Antonio Armijo and Orville Pratt: University of Nebraska Press, 375 p.

Harrill, James R., 1976, Pumping and ground-water storage depletion in Las Vegas Valley, Nevada, 1955–74: Nevada Department of Conservation and Natural Resources, Division of Water Resources Bulletin No. 44, 70 p.

Holzer, T.L., 1979, Leveling data—Eglington fault scarp, Las Vegas Valley, Nevada: U.S. Geological Survey Open-File Report 79-950, 7 p.

— 1984, Ground failure induced by ground-water withdrawal from unconsolidated sediment, in Holzer, T.L., ed., Man-induced land subsidence: Geological Society of America Reviews in Engineering Geology, v. 6, 221 p.

Houghton, J. G., Sakamoto, C. M., and Gifford, R.O., 1975, Nevada's weather and climate: Nevada Bureau of Mines and Geology Special Publication 2, 78 p.

Jones, F. L., and Cahlan, J. F. 1975, Water, a history of Las Vegas—Volume I: Las Vegas Valley Water District, 171 p.

Livingston, Penn, 1941, Underground leakage from artesian wells in the Las Vegas area, Nevada: U.S. Geological Survey Water-Supply Paper 849-D, p. 147–173.

Malmberg, G. T., 1965, Available water supply of the Las Vegas ground-water basin, Nevada: U.S. Geological Survey Water-Supply Paper 1780, 116 p., 13 plates.

Maxey, G.B., and Jameson, C.H., 1948, Geology and water resources of Las Vegas, Pahrump, and Indian Springs Valleys, Clark and Nye Counties, Nevada: Nevada State Engineer Water Resources Bulletin 5, 121 p.

Mendenhall, W.C., 1909, Some desert watering places in southeastern California and southwestern Nevada: U.S. Geological Survey Water-Supply Paper 224, 98 p.

Mifflin, M.D., and Wheat, M.M., 1979, Pluvial lakes and estimated pluvial climates of Nevada: Nevada Bureau of Mines and Geology Bulletin 94, 57 p., 1 plate.

Mindling, A.L., 1971, A summary of data relating to land subsidence in Las Vegas Valley: Center for Water Resources Research, Desert Research Institute, University of Nevada, Reno; 55 p.

Morgan, D.S., and Dettinger, M.D., 1996, Ground-water conditions in Las Vegas Valley, Clark County, Nevada, part 2, Hydrogeology and simulation of ground-water flow: U.S. Geological Survey Water-Supply Paper 2320-B, 124 p., 2 plates.

Nevada Department of Conservation and Natural Resources, Division of Water Resources and Water Planning, 1992, Hydrographic basin summaries, 1990–1992, [variously paged].

Plume, R. W., 1989, Ground-water conditions in Las Vegas Valley, Clark County, Nevada, part I, Hydrogeologic framework: U.S. Geological Survey Water-Supply Paper 2320-A, 15 p.

Quade, J., Mifflin, M.D., Pratt, W.L., McCoy, W., and Burckle, L., 1995, Fossil spring deposits in the southern Great Basin and their implications for change in water-table levels near Yucca Mountain, Nevada, during Quaternary time: Geological Society of America Bulletin, v. 107, p. 213–230.

Riley, F.S., 1969, Analysis of borehole extensometer data from central California: International Association of Scientific Hydrology Publication 89, p. 423–431.

U.S. Department of Commerce, 1997, Las Vegas metro area leads nation in population growth, census bureau reports: Bureau of the Census, accessed July 27, 1999, at URL http://www.census.gov/ftp/pub/Press-Release/cb97-212.html

Water Resources Management Incorporated, 1992, WRMI process—Water supply planning for the Las Vegas region, Columbia, Md., [25+] p.

SOUTH-CENTRAL ARIZONA

Anderson, S.R., 1988, Potential for aquifer compaction, land subsidence, and earth fissures in the Tucson Basin, Pima County, Arizona: U.S. Geological Survey Hydrologic Investigations Atlas 713, 3 sheets, scale 1:250,000.

Anderson, S.R., 1989, Potential for aquifer compaction, land subsidence, and earth fissures in Avra Valley, Pima and Pinal Counties, Arizona: U.S. Geological Survey Hydrologic Investigations Atlas 718, 3 sheets, scale 1:250,000.

Anderson, T.W., Freethey, G.W., and Tucci, P., 1992, Geohydrology and water resources of alluvial basins in south-central Arizona and parts of adjacent states: U.S. Geological Survey Professional Paper 1406-B, 67 p., 3 plates, scale 1:1,000,000.

Anning, D.W., and Duet, N.R., 1994, Summary of ground-water conditions in Arizona, 1987–90: U.S. Geological Survey Open-File Report 94-476, 2 sheets.

Arizona Department of Water Resources, 1999, Arizona water information, statewide overview, supply and demand (1994): accessed July 27, 1999 at URL http://www.adwr.state.az.us/AZWaterInfo/statewide/supplyde.html.

Carpenter, M.C., 1993, Earth-fissure movements associated with fluctuations in ground-water levels near the Picacho Mountains, south-central Arizona, 1980–84: U.S. Geological Survey Professional Paper 497-H, 49 p.

Carpenter, M.C., and Bradley, M.D., 1986, Legal perspectives on subsidence caused by ground-water withdrawal in Texas, California, and Arizona, U.S.A.: International Symposium on Land Subsidence, 3rd, Venice, 1984, [Proceedings, Johnson, A.I., Carbognin Laura, and Ubertini, L., eds.], International Association of Scientific Hydrology Publication 151, p. 817–828.

City of Tucson Water Department, 1995, Annual static water level basic data report, Tucson Basin and Avra Valley, Pima County, Arizona, 1995: City of Tucson Water Planning and Engineering Division, 140 p.

Eaton, G.P., Peterson, D.L., and Schumann, H.H., 1972, Geophysical, geohydrological, and geochemical reconnaissance of the Luke salt body, Central Arizona: U.S. Geological Survey Professional Paper 753, 28 p.

Feth, J.H., 1951, Structural reconnaissance of the Red Rock quadrangle, Arizona: U.S. Geological Survey Open-File Report, 30 p.

Holzer, T.L., 1980, Reconnaissance maps of earth fissures and land subsidence, Bowie and Willcox areas, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-1156, 2 sheets, scale 1:24,000.

Holzer, T.L., 1984, Ground failure induced by ground-water withdrawal from unconsolidated sediment, in Holzer, T.L., ed., Man-induced land subsidence: Geological Society of America Reviews in Engineering Geology, v. 6, p. 67–105.

Holzer, T.L., Davis, S.N., and Lofgren, B.E., 1979, Faulting caused by groundwater extraction in south-central Arizona: Journal of Geophysical Research, v. 84, p. 603-612.

Johnson, N.M., 1980, The relation between ephemeral stream regime and earth fissuring in south-central Arizona: Tucson, Ariz., University of Arizona, M.S. thesis, 158 p.

Laney, R.L., Raymond, R.H., and Winikka, C.C., 1978, Maps showing water-level declines, land subsidence, and earth fissures in south-central Arizona: U.S. Geological Survey Water-Resources Investigations Report 78-83, 2 sheets, scale 1:125,000.

Leonard, R.J., 1929, An earth fissure in southern Arizona: Journal of Geology, v. 37, p. 765-774.

Peterson, D.E., 1962, Earth fissuring in the Picacho area, Pinal County, Arizona: Tucson, Ariz., University of Arizona, M.S. thesis, 35 p.

Robinson, G.M., and Peterson, D.E., 1962, Notes on earth fissures in southern Arizona: U.S. Geological Survey Circular 466, 7 p.

Schumann, H.H., 1995, Land subsidence and earth fissure hazards near Luke Air Force Base, Arizona: in Prince, K.R., Galloway, D.L., and Leake, S.A., eds., U.S. Geological Survey subsidence interest group conference, Edwards Air Force Base, Antelope Valley, California, November 18–19, 1992—abstracts and summary: U.S. Geological Open-File Report 94-532, p. 18-21.

Schumann, H.H., and Cripe, L.S., 1986, Land subsidence and earth fissures caused by groundwater depletion in southern Arizona, U.S.A.: International Symposium on Land Subsidence, 3rd, Venice, 1984, [Proceedings, Johnson, A.I., Carbognin Laura, and Ubertini, L., eds.], International Association of Scientific Hydrology Publication 151, p. 841–851.

Schumann, H.H., and Genauldi, R.B., 1986, Land subsidence, earth fissures, and water-level change in southern Arizona: Arizona Bureau of Geology and Mineral Technology Geological Survey Branch Map 23, 1 sheet, scale 1:1,000,000.

Schumann, H.H., and Poland, J.F., [1969–1970], Land subsidence, earth fissures, and groundwater withdrawal in south-central Arizona, U.S.A: International Association of Scientific Hydrology Publication 88, p. 295–302.

Strange, W.E., 1983, Subsidence monitoring for the State of Arizona: National Oceanic and Atmospheric Administration National Geodetic Information Center, Rockville, Md., 80 p.

PART II—Drainage of Organic Soils

INTRODUCTION

Darby, H.C., 1956, The Draining of the Fens (2nd ed.): Oxford, Cambridge University Press, 314 p.

Lucas, R.E., 1982, Organic soils (Histosols)—Formation, distribution, physical and chemical properties and management for crop production: Michigan State University Farm Science Research Report 435, 77 p.

Nieuwenhuis, H.S., and Schokking, F., 1997, Land subsidence in drained peat areas of the Province of Friesland, The Netherlands: Quarterly Journal of Engineering Geology, v. 30, p. 37–48.

Schothorst, C.J., 1977, Subsidence of low moor peat soils in the western Netherlands: Geoderma, v. 17, p. 265–291.

Stephens, J.C., Allen, L.H., Jr., and Chen, Ellen, 1984, Organic soil subsidence *in* Holzer, T.L., ed., Man-induced land subsidence: Geological Society of America Reviews in Engineering Geology, v. 6, p. 107–122.

Waksman, S.A., and Purvis, E.R., 1932, The influence of moisture upon the rapidity of decomposition of lowmoor peat: Soil Science, v. 34, p. 323–336.

Waksman, S.A., and Stevens, K.R., 1929, Contribution to the chemical composition of peat, part 5. The role of microorganisms in peat formation and decomposition: Soil Science, v. 28, p. 315–340.

Wosten, J.H.M., Ismail, A.B., and van Wijk, A.L.M., 1997, Peat subsidence and its practical implications: A case study in Malaysia: Geoderma, v. 78, p. 25–36.

SACRAMENTO-SAN JOAQUIN DELTA, CALIFORNIA

Atwater, B.F., 1980, Attempts to correlate Late Quaternary climatic records between the San Francisco Bay, the Sacramento-San Joaquin Delta, and the Mokelumne River, California: Dover, Del., University of Delaware, Ph.D. dissertation, 215 p.

California Department of Water Resources, 1993, Sacramento-San Joaquin Delta atlas: Sacramento, State of California Department of Water Resources, 121 p.

California Department of Water Resources, 1995, Delta levees: Sacramento, State of California Department of Water Resources, 19 p.

Delta Protection Commission, 1995, Land use and resource management plan for the primary zone of the Delta: Walnut Grove, Delta Protection Commission, 60 p.

Deverel, S.J., and Rojstaczer, S.A., 1996, Subsidence of agricultural lands in the Sacramento-San Joaquin Delta, California: Role of aqueous and gaseous carbon fluxes: Water Resources Research, v. 32, p. 2,359-2,367.

Dillon, Richard, 1982, Delta Country: Novato, Calif., Presidio Press, 134 p.

Rojstaczer, S.A., and Deverel, S.J., 1993, Time dependence of atmospheric carbon inputs from drainage of organic soils: Geophysical Research Letters, v. 20, p. 1,383–1,386.

Rojstaczer, S.A., Hamon, R.E., Deverel, S.J., and Massey, C.A., 1991, Evaluation of selected data to assess the causes of subsidence in the Sacramento-San Joaquin Delta, California: U.S. Geological Survey Open-File Report 91-193, 16 p.

Tans, P.P., Fung, I.Y., and Takahashi, Y., 1990, Observational constraints on the global atmospheric CO2 budget: Science, v. 247, p. 1,431–1,438.

Thompson, John, 1957, The settlement geography of the Sacramento-San Joaquin Delta, California: Palo Alto, Calif., Stanford University, Ph.D. dissertation, 551 p.

Weir, W.W., 1950, Subsidence of peat lands of the Sacramento-San Joaquin Delta, California: Hilgardia, v. 20, p. 37–55.

FLORIDA EVERGLADES

Allison, R.V., 1956, The influence of drainage and cultivation on subsidence of organic soils under conditions of Everglades reclamation: Soil and Crop Science Society of Florida Proceedings, v. 16, p. 21–31.

Bodle, M.J., Ferriter, A.P., and Thayer, D.D., 1994, The biology, distribution, and ecological consequences of Melaleuca quinquenervia in the Everglades, *in* Davis, S.M., and Ogden, J.C., The Everglades—The ecosystem and its restoration: Delray Beach, Fla.,St. Lucie Press, p. 341–355.

Craft, C.B., and Richardson, C.J., 1993a, Peat accretion and N, P, and organic C accumulation in nutrient-enriched and unenriched Everglades peatlands: Ecological Applications, v. 3, p. 446–458.

Craft, C.B., and Richardson, C.J., 1993b, Peat accretion and phosphorus accumulation along a eutrophication gradient in the northern Everglades: Biogeochemistry, v. 22, p. 133–156.

Davis, J.R., Jr., 1946, The peat deposits of Florida: Florida Geological Survey Bulletin 30, 247 p.

Davis, S.M., and Ogden, J.C., eds., 1994, The Everglades—The ecosystem and its restoration: Delray Beach, Fla., St. Lucie Press, 826 p.

Deren, C.W., Snyder, G.H., Miller, J.D., and Porter, P.S., 1991, Screening for heritability of flood-tolerance in the Florida (CP) sugarcane breeding population: Euphytica, v. 56, p. 155–160.

Douglas, M.S., 1947, The Everglades— River of grass: St. Simons Island,Fla., Mockingbird Press, 308 p.

Gascho, G.J., and Shih, S.F., 1979, Varietal response of sugarcane to water table depth, part 1. Lysimeter performance and plant response: Soil and Crop Society of Florida Proceedings, v. 38, p. 23–27.

Glaz, Barry, 1995, Research seeking agricultural and ecological benefits in the Everglades: Journal of Soil and Water Conservation, v. 50, p. 609–612.

Johnson, Lamar, 1974, Beyond the fourth generation: Gainesville, Fla., The University Presses of Florida, 230 p.

Jones, L.A., Allison, R.V., and others, 1948, Soils, geology, and water control in the Everglades region: University of Florida Agricultural Experiment Station Bulletin 442, 168 p., 4 maps.

Kang, M.S., Snyder, G.H., and Miller, J.D., 1986, Evaluation of Saccharum and related germplasm for tolerance to high water table on organic soil: Journal of the American Society of Sugar Cane Technologists, v. 6, p. 59–63.

Light, S.S., and Dineen, J.W., 1994, Water control in the Everglades: A historical perspective, in Davis, S.M., and Ogden, J.C., The Everglades—The ecosystem and its restoration: Delray Beach, Fla., St. Lucie Press, p. 47–84.

Lucas, R.E., 1982, Organic soils (Histosols)—Formation, distribution, physical and chemical properties and management for crop production: Michigan State University Farm Science Research Report 435, 77 p.

Matson, G.C., and Sanford, Samuel, 1913, Geology and ground water of Florida: U.S. Geological Survey Water-Supply Paper 319, 445 p.

McIvor, C.C., Ley, J.A., and Bjork, R.D., 1994, Changes in freshwater inflow from the Everglades to Florida Bay including effects on biota and biotic processes: A review, in Davis, S.M., and Ogden, J.C., The Everglades—The ecosystem and its estoration: Delray Beach, Fla., St. Lucie Press, p. 117–146.

Ogden, J.C., 1994, A comparison of wading bird nesting colony dynamics (1931–1946 and 1974–1989) as an indication of ecosystem conditions in the southern Everglades, in Davis, S.M., and Ogden, J.C., The Everglades—The ecosystem and its restoration: Delray Beach, Fla.,St. Lucie Press, p. 533–570.

Porter, G.S., Snyder, G.H., and Deren, C.W., 1991, Flood-tolerant crops for low input sustainable agriculture in the Everglades agricultural area: Journal of Sustainable Agriculture, v. 2, p. 77–101.

Ray, J.D., Miller, J.D., and Sinclair, T.R., 1996, Survey of arenchyma in sugarcane roots (abs.): Fifth Symposium of the International Society of Root Research, July 14–18, 1996, Clemson, S. C., p. 118.

Shih, S.F., Glaz, Barry, and Barnes, R.E., Jr., 1997, Subsidence lines revisited in the Everglades agricultural area, 1997: University of Florida Agricultural Experiment Station Bulletin 902, 38 p.

Shih, S.F., Stewart, E.H., Allen, L.H., Jr., and Hilliard, J.E., 1979, Variability of depth to bedrock in Everglades organic soil: Soil and Crop Society of Florida Proceedings, v. 38, p. 66–71.

Smith, G., 1990, The Everglades agricultural area revisited: Citrus and Vegetable Magazine, v. 53, no. 9, p. 40-42.

Smith, T.S., and Bass, O.L., Jr., 1994, Landscape, white-tailed deer, and the distribution of Florida panthers in the Everglades, in Davis, S.M., and Ogden, J.C., The Everglades—The ecosystem and its restoration: Delray Beach, Fla., St. Lucie Press, p. 693–708.

Snyder, G.H., and Davidson, J.M., 1994, Everglades agriculture: Past, present, and future, in Davis, S.M., and Ogden, J.C., The Everglades—The ecosystem and its restoration: Delray Beach, Fla., St. Lucie Press, p. 85–115.

Stephens, J.C., Allen, L.H., Jr., and Chen, Ellen, 1984, Organic soil subsidence, in Holzer, T.L., ed., Man-induced land subsidence: Geological Society of America Reviews in Engineering Geology, v. 6, p. 107–122.

Stephens, J.C., and Johnson, Lamar, 1951, Subsidence of organic soils in the upper Everglades region of Florida: Soil Science Society of Florida Proceedings, v. 11, p. 191–237.

PART III—Collapsing Cavities

INTRODUCTION

Ege, J.R. 1984, Mechanisms of surface subsidence resulting from solution extraction of salt, *in* Holzer, T.L. ed., Man-induced land subsidence: Geological Society of America Reviews in Engineering Geology, v. 6, p. 203–221.

Martinez, J.D., Johnson, K.S., and Neal, J.T., 1998, Sinkholes in evaporite rocks: American Scientist, v. 86, p. 38–51.

White, W.B., Culver, D.C., Herman, J.S., Kane, T.C., and Mylroie, J.E., 1995, Karst lands: American Scientist, v. 83, p. 450–459.

THE RETSOF SALT MINE COLLAPSE, NEW YORK

Alpha Geoscience, 1996, Geologic and hydrogeologic investigation of the Genesee River Valley, prepared for AKZO Nobel Salt Inc., Clarks Summit, Pa.,: Albany, N. Y., Alpha Geoscience Project no. 95132, 31 p., 10 app., 4 plates.

Dunn Corporation, 1992, Hydrogeologic report for the AKZO ash processing plant: Report to Akzo Nobel Salt, Inc., Clarks Summit, Pa., 35 p.

Moran, R.P., Scovazzo, V.A., and Streib, D.L., 1995, Impact analysis—Retsof Mine, Akzo Nobel Salt, Inc.: Report 2455, prepared for the New York State Department of Conservation, J.T. Boyd Co., Inc., 54 p.

Nittany Geoscience, 1995, Groundwater recharge calculations for the Retsof Mine: May 12, 1995, Letter Report, 6 p.

NYSDEC (New York State Department of Environmental Conservation), 1997, Collapse and flooding of Akzo Nobel's Retsof salt mine, Livingston Co., N. Y.: Feb. 1997 Draft report of the Department Task Force, Feb. 1997, 114 p.

Riley, F.S., 1969, Analysis of borehole extensometer data from central California, International Association Of Scientific Hydrology Publication 89, p. 423–431.

Shannon and Wilson, Inc., 1997, Task 3, final report—Retsof Mine collapse, Technical Assistance Grant Committee, Retsof, New York: Seattle, Wash., Shannon and Wilson Inc., 15 p.

Van Sambeek, L.L., 1994, Predicted ground settlement over the Akzo Nobel Retsof Mine, prepared for Akzo Nobel Salt Inc., Clarks Summit, Pa., Project RSI-0525: Rapid City, S. Dak., RE/SPEC Inc., [27+] p.

Van Sambeek, L.L., 1996, Dissolution-induced mine subsidence at the Retsof Salt Mine: Meeting Paper, Solution Mining Research Institute, October 20–23, 1996, Cleveland, Ohio, p. 289–309.

Young, R.A., 1975, The effects of a Late Wisconsin glacial readvance on the postglacial geology of the Genesee Valley, Livingston County, N. Y. [abs.]: Geological Society of America Abstracts with Programs, v. 7, p. 135–136.

SINKHOLES, WEST-CENTRAL FLORIDA

Atkinson, T., 1977, Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain): Journal of Hydrology, v. 35, p. 93–110.

Bengtsson, T.O., 1987, The hydrologic effects from intense ground-water pumpage in east-central Hillsborough County, Florida, *in* Beck, B.F. and Wilson, W.L. eds, Karst hydrogeology: engineering and environmental applications: proceedings of a conference sponsored by the Florida Sinkhole Research Institute, February 9–11, 1987, College of Engineering, University of Central Florida, Orlando: Boston, Mass., A.A. Balkema, p. 109–114.

Brooks, H.K., 1981, Guide to the physiographic divisions of Florida: Gainesville, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, 11 p., 1 plate.

Brucker, R.W., Hess, J.W., and White, W.B., 1972, Role of vertical shafts in the movement of ground water in carbonate aquifers: Ground Water, v. 10, p. 5–13.

Culshaw, M.G., and Waltham, A.C., 1987, Natural and artificial cavities as ground engineering hazards: Quarterly Journal of Engineering Geology, v. 20. p. 139–150.

Ford, D., and Williams, P., 1989, Karst Geomorphology and Hydrology: Boston, Mass., Unwin Hyman, 601 p.

Lattman, L.H., and Parizek, R.R., 1964, Relationship between fracture traces and the occurrence of ground water in carbonate rocks: Journal of Hydrology, v. 2, p. 73–91.

Lewelling, B. R., Tihansky, A. B., and Kindinger, J. L., 1998, Assessment of the hydraulic connection between ground water and the Peace River, west-central Florida: U. S. Geological Survey Water-Resources Investigation Report 97-4211, 96 p.

Littlefield, J.R., Culbreth, M.A., Upchurch, S.B., and Stewart, M.T., 1984, Relationship of modern sinkhole development to large-scale photolinear features: Multidisciplinary Conference on Sinkholes, 1st, Orlando, Fla., October 15–17, [Proceedings, Beck, B.F., ed., Sinkholes—Their geology, engineering and environmental impact: Boston, Mass., A.A. Balkema], p. 189–195.

Metcalfe, S.J., and Hall, L.E., 1984, Sinkhole collapse due to groundwater pumpage for freeze protection irrigation near Dover, Florida, January, 1977: Multidisciplinary Conference on Sinkholes, 1st, Orlando, Florida, October 15–17, [Proceedings, Beck, B.F., ed., Sinkholes—Their geology, engineering and environmental impact: Boston, Mass., A.A. Balkema], p. 29–33.

Mularoni, R. A., 1993, Potentiometric surface of the Upper Floridan Aquifer, west-central Florida, September 1992: U. S. Geological Survey Open-File Report 93-49, 1 plate.

Newton, J.G., 1986, Development of sinkholes resulting from man's activities in the eastern United States: U.S. Geological Survey Circular 968, 54 p.

Quinlan, J.F., Davies, G.J., and Worthington, S.R.,1993, Review of groundwater quality monitoring network design: Journal of Hydraulic Engineering, v. 119, p. 1,436–1,441. [Discussion, with reply, p. 1,141–1,142]

Ryder, P.D., 1985, Hydrology of the Floridan aquifer system in west-central Florida: U.S. Geological Survey Professional Paper 1403-F, 63 p., 1 plate.

Sinclair, W.C., 1982, Sinkhole development resulting from ground-water development in the Tampa area, Florida: U.S. Geological Survey Water-Resources Investigations Report 81-50, 19 p.

Sinclair, W.C., and Stewart, J.W., 1985, Sinkhole type, development, and distribution in Florida: U.S. Geological Survey Map Series 110, 1 plate.

Southeastern Geological Society, 1986, Hydrogeological Units of Florida: Florida Geological Survey Special Publication 28, 9 p.

Sowers, G.F., 1984, Correction and protection in limestone terrane: Multidisciplinary Conference on Sinkholes, 1st, Orlando, Florida, October 15–17, [Proceedings, Beck, B.F., ed., Sinkholes—Their geology, engineering and environmental impact: Boston, Mass., A.A. Balkema], p. 373–378.

Stewart, M., and Parker, J., 1992, Localization and seasonal variation of recharge in a covered karst aquifer system, Florida, USA: International Contributions to Hydrogeology, v. 13, Springer-Verlag, p. 443–460.

Tihansky, A.B., and Trommer, J. T., 1994, Rapid ground-water movement and transport of nitrate within a karst aquifer system along the coast of west-central Florida [abs.]: Transactions American Geophysical Union, v. 75, April 19, 1994—Supplement, p. 156.

Trommer, J.T., 1992, Effects of effluent spray irrigation and sludge disposal on ground water in a karst region, northwest Pinellas County, Florida: U.S. Geological Survey Water-Resources Investigations Report 91-4181, 32 p.

Watts, W.A., 1980, The Late Quaternary vegetation history of the southeastern United States: Annual Review of Ecology and Systematics, v. 11, p. 387–409.

Watts, W.A., and Stuiver, M., 1980, Late Wisconsin climate of northern Florida and the origin of species-rich deciduous forest: Science, v. 210, p. 325–327.

Watts, W.A., and Hansen, B.C.S., 1988, Environments of Florida in the Late Wisconsinan and Holocene, *in* Purdy, B.A., ed., Wet site archeology: Caldwell, N.J., Telford West, p. 307–323.

White, W.A.,1970, The geomorphology of the Florida peninsula: Florida Bureau of Geology Geological Bulletin 51, 164 p.

Wilson, W.L., and Shock, E.J., 1996, New sinkhole data spreadsheet manual (v1.1): Winter Springs, Fla., Subsurface Evaluations, Inc., 31 p., 3 app., 1 disk.

The Role of Science

Amelung, F., Galloway, D.L., Bell, J.W., Zebker, H.A., and Laczniak, R.J., 1999, Sensing the ups and downs of Las Vegas—InSAR reveals structural control of land subsidence and aquifer-system deformation: Geology, v. 27, p. 483–486.

Anderson S.R., 1988, Potential for aquifer compaction, land subsidence, and earth fissures in Tucson Basin, Pima County, Arizona: U.S. Geological Survey Hydrologic Investigations Atlas HA-713, 3 sheets, scale 1:250,000.

Anderson, S.R., 1989, Potential for aquifer compaction, land subsidence, and earth fissures in Avra Valley, Pima and Pinal Counties, Arizona: U.S. Geological Survey Hydrologic Investigations Atlas HA-718, 3 sheets, scale 1:250,000.

Bear, J., 1979, Hydraulics of groundwater: New York, McGraw-Hill, 569 p.

Biot, M.A., 1941, General theory of three-dimensional consolidation: Journal of Applied Physics, v. 12, p. 155–164.

Blomquist, W., 1992, Dividing the waters—Governing groundwater in southern California: San Francisco, Calif., ICS Press, 413 p.

Carpenter, M.C., 1993, Earth-fissure movements associated with fluctuations in ground-water levels near the Picacho Mountains, south-central Arizona, 1980–84: U.S. Geological Survey Professional Paper 497-H, 49 p.

Fielding, E.J., Blom, R.G., and Goldstein, R.M., 1998, Rapid subsidence over oil fields measured by SAR interferometry: Geophysical Research Letters, v. 27, p. 3,215–3,218.

Gabriel, A.K., Goldstein, R.M., and Zebker, H.A., 1989, Mapping small elevation changes over large areas—Differential radar interferometry: Journal of Geophysical Research, v. 94, p. 9,183–9,191.

Galloway, D.L., Hudnut, K.W., Ingebritsen, S.E., Phillips, S.P., Peltzer, G., Rogez, F., and Rosen, P.A., 1998, Detection of aquifer system compaction and land subsidence using interferometric synthetic aperture radar, Antelope Valley, Mojave Desert, California: Water Resources Research, v. 34, p. 2,573–2,585.

Hanson, R.T., 1989, Aquifer-system compaction, Tucson Basin and Avra Valley, Arizona: U.S. Geological Survey Open-File Report 88-4172, 69 p.

Hanson, R.T., Anderson, S.R., and Pool, D.R., 1990, Simulation of ground-water flow and potential land subsidence, Avra Valley, Arizona: U.S. Geological Survey Water-Resources Investigations Report 90-4178, 41 p.

Hanson, R.T., and Benedict, J.F., 1994, Simulation of ground-water flow and potential land subsidence, upper Santa Cruz Basin, Arizona: U.S. Geological Survey Water-Resources Investigations Report 93-4196, 47 p.

Helm, D.C., 1975, One-dimensional simulation of aquifer system compaction near Pixley, Calif., part 1. Constant parameters: Water Resources Research, v. 11, p. 465–478.

Helm, D.C., 1978, Field verification of a one-dimensional mathematical model for transient compaction and expansion of a confined aquifer system: American Society of Civil Engineers Hydraulics Division Specialty Conference, 26th, University of Maryland, College Park, Md., August 9–11, 1978, p. 189–196.

Heywood, C.E., 1995, Investigation of aquifer-system compaction in the Hueco basin, El Paso, Texas, USA: International Symposium on Land Subsidence, 5th, Delft, Netherlands, October 1995, International Association of Hydrological Sciences Publication 234, p. 35–45.

Holzer, T.L., 1981, Preconsolidation stress of aquifer systems in areas of induced land subsidence: Water Resources Research, v. 17, p. 693–704.

Ikehara, M.E., Galloway, D.L., Fielding, E., Bürgmann, R., Lewis, A.S., and Ahmadi, B., 1998, InSAR imagery reveals seasonal and longer-term land-surface elevation changes influenced by ground-water levels and fault alignment in Santa Clara Valley, California [abs.]: EOS (supplement) Transactions, American Geophysical Union, no. 45, November 10, 1998, p. F37.

Ikehara, M.E., and Phillips, S.P., 1994, Determination of land subsidence related to ground-water level declines using global positioning system and leveling surveys in Antelope Valley, Los Angeles and Kern Counties, California, 1992: U.S. Geological Survey Water-Resources Investigations Report 94-4184, 101 p.

Massonnet, D., Briole, P., and Arnaud, A., 1995, Deflation of Mount Etna monitored by spaceborne radar interferometry: Nature, v. 375, p. 567–570.

Massonnet, D., and Feigl, K.L., 1998, Radar interferometry and its application to changes in the earth's surface: Reviews of Geophysics, v. 36, p. 441–500.

Massonnet, D., Holzer, T., and Vadon, H., 1997, Land subsidence caused by the East Mesa geothermal field, California, observed using SAR interferometry: Geophysical Research Letters, v. 24, p. 901–904.

Massonnet, D., Rossi, M., Carmona, C., Adragna, F., Peltzer, G., Feigl, K., and Rabaute, T., 1993, The displacement field of the Landers earthquake mapped by radar interferometry: Nature, v. 364, p. 138–142.

National Research Council, 1991, Mitigating losses from land subsidence in the United States: Washington, D. C., National Academy Press, 58 p.

Riley, F.S., 1969, Analysis of borehole extensometer data from central California, International Association of Scientific Hydrology Publication 89, p. 423–431.

Riley, F.S., 1986, Developments in borehole extensometry: International Symposium on Land Subsidence, 3rd, Venice, 19–25 March 1984, [Proceedings, Johnson, I.A., Carborgnin, Laura, and Ubertini, L., eds.], International Association of Scientific Hydrology Publication 151, p. 169–186.

Rosen, P.A., Hensley, S., Zebker, H.A., Webb, F.H., and Fielding, E., 1996, Surface deformation and coherence measurements of Kilauea volcano, Hawaii, from SIR-C radar interferometry: Journal of Geophysical Research, v. 101, p. 23,109–23,125.

Tihansky, A.B., Arthur, J.D., and DeWitt, D.J., 1996, Sublake geologic structure from high-resolution seismic-reflection data from four sinkhole lakes in the Lake Wales Ridge, Central Florida: U.S. Geological Survey Open-File Report 96-224, 72 p.

Terzaghi, K., 1925, Principles of soil mechanics, IV—Settlement and consolidation of clay: Engineering News-Record, v. 95, p. 874–878.

Vadon, H., and Sigmundsson, F., 1997, 1992–1995 crustal deformation at Mid-Atlantic ridge, SW Iceland, mapped by radar interferometry: Science, v. 275, p. 193–197.

Wicks, C., Jr., Thatcher, W., and Dzurisin, D., 1998, Migration of fluids beneath Yellowstone Caldera inferred from satellite radar interferometry: Science, v. 282, p. 458–462.

Zebker, H.A., Rosen, P.A., Goldstein, M., Gabriel, A., and Werner, C.L., 1994, On the derivation of coseismic displacement fields, using differential radar interferometry—The Landers earthquake: Journal of Geophysical Research, v. 99, p. 19,617–19,634.

Zilkoski, D.B., D'Onofrio, J.D., and Frakes, S.J., 1997, Guidelines for establishing GPS-derived ellipsoid heights (Standards: 2 cm and 5 cm), ver. 4–3: National Oceanic and Atmospheric Administration Technical Memorandum NOS NGS-58, [20+] p.

UNITED STATES GEOLOGICAL SURVEY

SELECTED PUBLICATIONS AND AVAILABILITY

PUBLICATIONS

Books and other publications

Professional Papers report scientific data and interpretations of lasting scientific interest that cover all facets of USGS investigations and research.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars are reports of programmatic of scientific information of an ephemeral nature; many present important scientific information of wide popular interest. Circulars are distributed at no cost to the public.

Fact Sheets communicate a wide variety of timely information on USGS programs, projects, and research. They commonly address issues of public interest. Fact sheets generally are two or four pages long and are distributed at no cost to the public.

Reports in the **Digital Data Series (DDS)** distribute large amounts of data through digital media, including compact disc-read-only memory (CD-ROM). They are high-quality, interpretive publications designed as self-contained packages for viewing and interpreting data and typically contain data sets, software to view the data, and explanatory text.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are produced on request (unlike formal USGS publications) and are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports can consist of basic data, preliminary reports, and a wide range of scientific documents of USGS investigations. Open-File Reports are designed for fast release and are available for public consultation at depositories.

Maps

Geologic Quadrangle Maps (GQs) are multicolor geologic maps on topographic bases in 7.5- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar section only.

Geophysical Investigations Maps (GPs) are on topographic or planimetric bases at various scales. They show results of geophysical investigations using gravity, magnetic, seismic, or radioactivity surveys, which provide data on subsurface structures that are of economic or geologic significance.

Miscellaneous Investigations Series Maps or **Geologic Investigations Series** (**Is** are on planimetric or topographic bases at various scales; they present a wide variety of format and subject matter. The series also includes 7.5-minute quadrangle photogeologic maps on planimetric bases and planetary maps.

Information Periodicals

Metal Industry Indicators (MIIs) is a free monthly newsletter that analyzes and forecasts the economic health of five metal industries with composite leading and coincident indexes: primary metals, steel, copper, primary and secondary aluminum, and aluminum mill products.

Mineral Industry Surveys (MISs) are free periodic statistical and economic reports designed to provide timely statistical data on production, distribution, stocks, and consumption of significant mineral commodities. The surveys are issued monthly, quarterly, annually, or at other regular intervals, depending on the need for current data. The MISs are published by commodity as well as by State. A series of international MISs is also available.

Published on an annual basis, **Mineral Commodity Summaries** is the earliest Government publication to furnish estimates covering nonfuel mineral industry data. Data sheets contain information on the domestic industry structure, government programs, tariffs, and 5-year salient statistics for more than 90 individual mineral and materials.

The Minerals Yearbook discusses the performance of the worldwide minerals and materials industry during a calendar year, and it provides background information to assist in interpreting that performance. The Minerals Yearbook consists of three volumes. Volume I, Metals and Minerals, contains chapters about virtually all metallic and industrial mineral commodities important to the U.S. economy. Volume II, Area Reports: Domestic, contains a chapter on the minerals industry of each of the 50 states and Puerto Rico and the Administered Islands. Volume III, Area Reports: International, is published as four separate reports. These reports collectively contain the latest available mineral data on more than 190 foreign countries and discuss the importance of minerals to the economies of these nations and the United States.

Permanent Catalogs

"Publications of the U.S. Geological Survey, 1879–1961" and **"Publications of the U.S. Geological Survey, 1962–1970"** are available in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971–1981" is available in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Annual supplements for 1982, 1983, 1984, 1985, 1986, and subsequent years are available in paperback book form.

AVAILABILITY OF PUBLICATIONS

Order U.S. Geological Survey (USGS) publications by calling the toll-free telephone number 1-888-ASK-USGS or contacting the offices listed below. Detailed ordering instructions, along with prices of the last offerings, are given in the current-year issues of the catalog "New Publications of the U.S. Geological Survey."

Books, Maps, and Other Publications

By Mail

Books, maps and other publications are available my mail from:

USGS Information Series
Box 25286, Federal Center
Denver, CO 80225

Publications include Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, Fact Sheets, publications of general interest, single copies of permanent USGS catalogs, and topographic and thematic maps.

Over the Counter

Books, maps, and other publications of the U.S. Geological Survey are available over the counter at the following USGS Earth Science Information Centers (ESICs), all of which are authorized agents of the Superintendent of Documents:

- Anchorage, Alaska—Rm. 101, 4230 University Dr.
- Denver, Colorado—Bldg. 810, Federal Center
- Menlo Park, California—Rm. 3128, Bldg. 3, 345 Middlefield Rd.
- Reston, Virginia—1C402, USGS National Center, 12201 Sunrise Valley Dr.
- Salt Lake City, Utah—2222 West, 2300 South
- Spokane, Washington—Rm. 135, U.S. Post Office Building, 904 West Riverside Ave.
- Washington, D.C.—Rm. 2650, Main Interior Bldg., 18th and C Sts., NW

Maps only may be purchased over the counter at the following USGS office:

- Rolla, Missouri—1400 Independence Rd.

Electronically

Some USGS publications, including the catalog "New Publications of the U.S. Geological Survey" are also available electronically on the USGS's World Wide Web home page at **http://www.usgs.gov**

Preliminary Determination of Epicenters

Subscriptions to the periodical "Preliminary Determination of Epicenters" can be obtained only from the Superintendent of Documents. Check or money order must be payable to the Superintendent of Documents. Order by mail from:

Superintendent of Documents
Government Printing Office
Washington, DC 20402

Information Periodicals

Many Information Periodicals products are available through the systems or formats listed below:

Printed Products

Printed copies of the Minerals Yearbook and the Mineral Commodity Summaries can be ordered from the Superintendent of Documents, Government Printing Office (address above). Printed copies of Metal Industry Indicators and Mineral Industry Surveys can be ordered from the Center for Disease Control and Prevention, National Institute for Occupational Safety and Health, Pittsburgh Research Center, P.O. Box 18070, Pittsburgh, PA 15236-0070

Mines FaxBack: Return fax service

1. Use the touch-tone handset attached to your fax machine's telephone jack. (ISDN [digital] telephones cannot be used with fax machines.)
2. Dial (703) 648-4999
3. Listen to the menu options and punch in the number of your selection, using the touch-tone telephone.
4. After completing your selection, press the start button on your fax machine.

CD-ROM

A disc containing chapters of the Minerals Yearbook (1993–95), the Mineral Commodity Summaries (1995–97), a statistically compendium (1970–90), and other publications is updated three times a year and sold by the Superintendent of Documents, Government Printing Office (address above).

World Wide Web

Minerals information is available electronically at **http://minerals.er.usgs.gov/minerals/**

Subscription to the catalog "New Publications of the U.S. Geological Survey"

Those wishing to be placed on a free subscription list for the catalog "New Publications of the U.S. Geological Survey" should write to:

U.S. Geological Survey
903 National Center
Reston, VA 20192