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Estimates of Hydraulic Properties from a One-Dimensional Numerical Model of Vertical Aquifer-System Deformation, Lorenzi Site, Las Vegas, Nevada

Water-Resources Investigations Report 03–4083

Prepared in cooperation with the
NEVADA DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES–DIVISION OF WATER RESOURCES
and LAS VEGAS VALLEY WATER DISTRICT

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By Michael T. Pavelko

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Carson City, Nevada
2004

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot (ft)	304.8	millimeter
feet per day (ft/d)	0.3048	meters per day
inch (in.)	2.54	centimeter
square mile (mi^2)	2.59	square kilometer

Temperature: Degrees Celsius (^oC) can be converted to degrees Fahrenheit (^oF) by using the formula $^oF = [1.8(^oC)]+32$. Degrees Fahrenheit can be converted to degrees Celsius by using the formula $^oC = 0.556(^oF-32)$.

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called “Sea-Level Datum of 1929”), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

Estimates of Hydraulic Properties from a One-Dimensional Numerical Model of Vertical Aquifer-System Deformation, Lorenzi Site, Las Vegas, Nevada

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ABSTRACT

Land subsidence related to aquifer-system compaction and ground-water withdrawals has been occurring in Las Vegas Valley, Nevada, since the 1930's, and by the late 1980's some areas in the valley had subsided more than 5 feet. Since the late 1980's, seasonal artificial-recharge programs have lessened the effects of summertime pumping on aquifer-system compaction, but the long-term trend of compaction continues in places.

Since 1994, the U.S. Geological Survey has continuously monitored water-level changes in three piezometers and vertical aquifer-system deformation with a borehole extensometer at the Lorenzi site in Las Vegas, Nevada. A one-dimensional, numerical, ground-water flow model of the aquifer system below the Lorenzi site was developed for the period 1901–2000, to estimate aquitard vertical hydraulic conductivity, aquitard inelastic skeletal specific storage, and aquitard and aquifer elastic skeletal specific storage. Aquifer water-level data were used in the model as the aquifer-system stresses that controlled simulated vertical aquifer-system deformation. Nonlinear-regression methods were used to calibrate the model, utilizing estimated and measured aquifer-system deformation data to minimize a weighted least-squares objective function, and estimate optimal property values.

Model results indicate that at the Lorenzi site, aquitard vertical hydraulic conductivity is 3×10^{-6} feet per day, aquitard inelastic skeletal specific storage is 4×10^{-5} per foot, aquitard elastic skeletal specific storage is 5×10^{-6} per foot, and aquifer elastic skeletal specific storage is 3×10^{-7} per foot. Regression statistics indicate that the model and data provided sufficient information to estimate the target properties, the model adequately simulated observed data, and the estimated property values are accurate and unique.

INTRODUCTION

Las Vegas, Nevada (fig. 1), is one of the fastest growing metropolitan areas in the United States and one of the hottest and most arid regions of the southwest. The rapid population growth has increased demand for water supplies. Las Vegas Valley relied almost entirely on ground water until the 1970's, when large volumes of Colorado River water began to be imported into the valley; by 2000, ground water accounted for less than 20 percent of water used in the valley (Coache, 2000). Ground-water withdrawals from the local alluvial aquifer system exceeded estimated natural recharge by the 1950's (Malmberg, 1965), and by 1980, resulted in water-level declines of more than 300 ft from predevelopment conditions in some areas of Las Vegas Valley (Burbey, 1995). Ground-water depletion has caused aquifer-system compaction, land subsidence, and earth fissuring (Maxey and Jameson, 1948; Malmberg, 1965; Bell, 1981). The land surface in some areas of Las Vegas

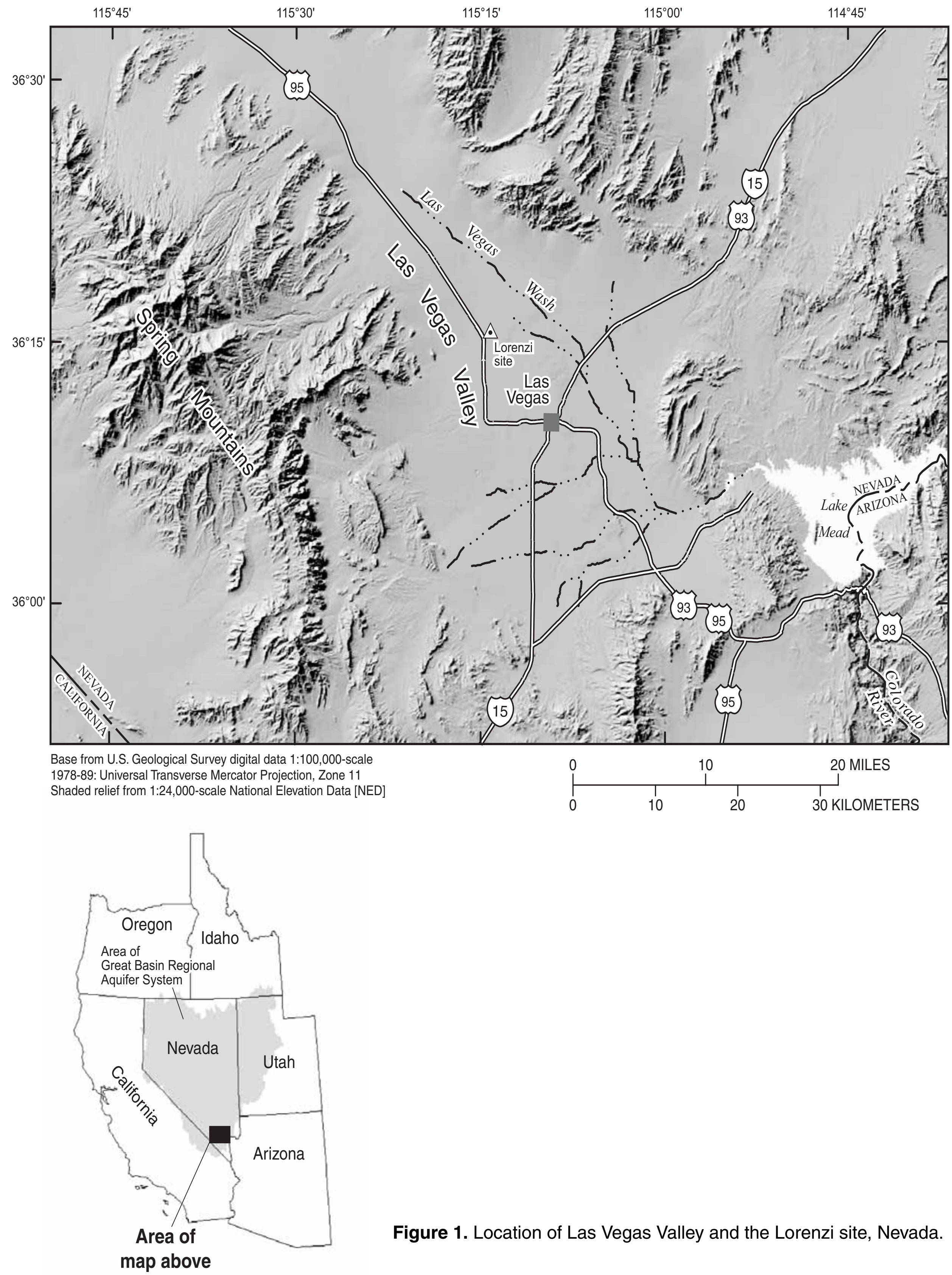


Figure 1. Location of Las Vegas Valley and the Lorenzi site, Nevada.

Valley has subsided more than 5 ft (Bell and Price, 1993, pl. 4) and damage to homes, roads, water lines, and wells have been attributed to associated earth fissures (Bell, 1981; Bell, 1997; Bell and Price, 1993). Since about 1988, water levels in some areas have stabilized or risen by as much as 100 ft (Wood, 2000), likely because of artificial-recharge programs initiated by the Las Vegas Valley Water District and the City of North Las Vegas that inject treated Colorado River water into the aquifer system. In areas where water levels have stabilized or risen, the rate of land subsidence has slowed, slight uplift during periods of artificial recharge has occurred, or both, but subsidence continues to occur and is the dominant long-term trend (Amelung and others, 1999; Pavelko, 2000; Hoffmann and others, 2001).

The U.S. Geological Survey (USGS) did this study in cooperation with the Nevada Department of Conservation and Natural Resources–Division of Water Resources and the Las Vegas Valley Water District (LVVWD) to develop a better understanding of the relations among land subsidence and uplift, vertical aquifer-system deformation, and ground-water-level fluctuations. As part of this effort, the Lorenzi site, in northwest Las Vegas (figs. 1 and 2), was established in 1994 to continuously measure vertical aquifer-system deformation and water levels (Pavelko, 2000). For this report, vertical deformation describes a change in the thickness of a horizontal aquifer-system unit. To better understand the aquifer-system mechanics, hydraulic properties were estimated using a one-dimensional (1-D) numerical model that simulated Lorenzi site ground-water levels and vertical aquifer-system deformation.

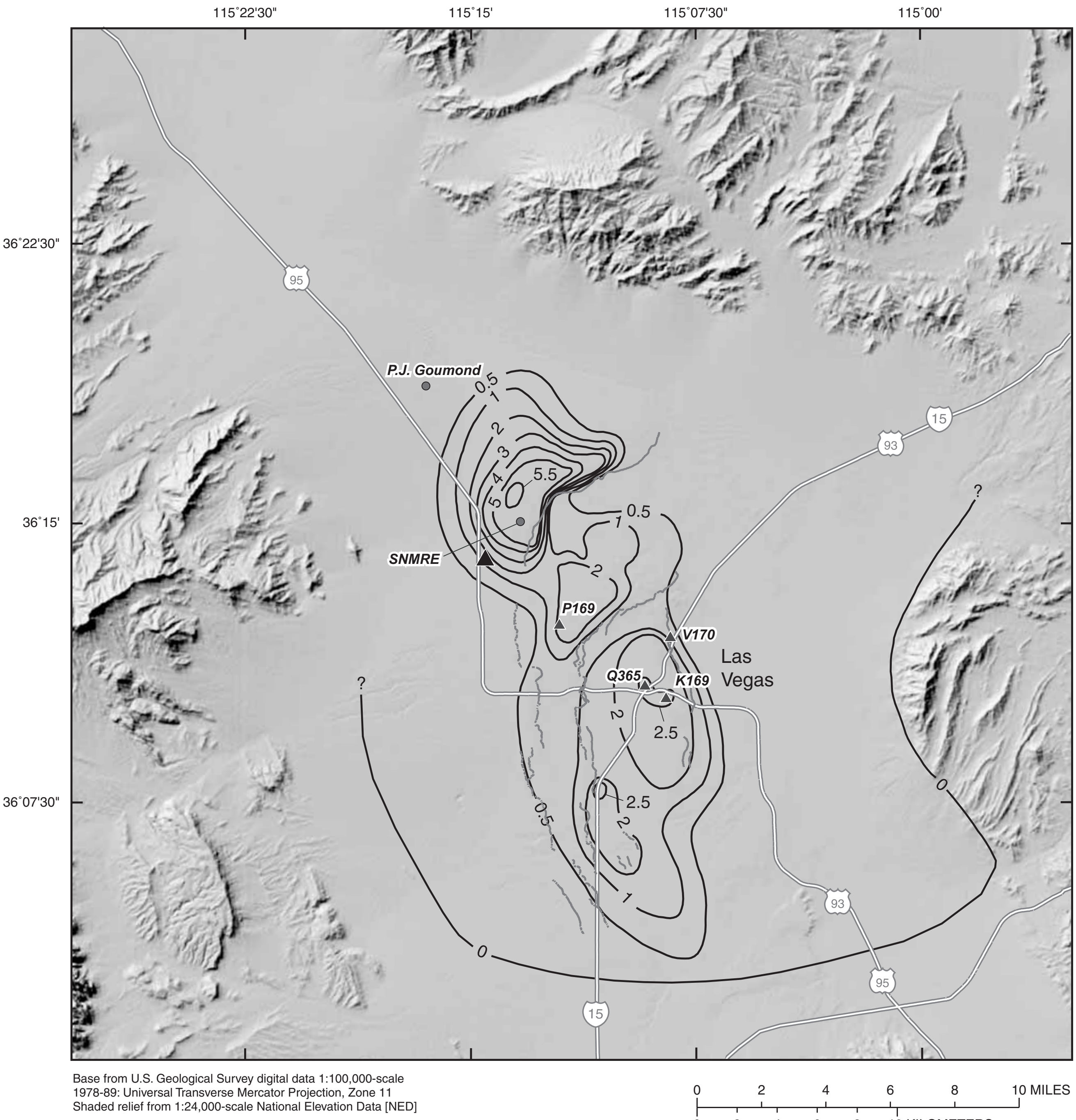
Subsidence and uplift refer to the sinking and rising of the land surface, respectively. In Las Vegas Valley, subsidence and uplift generally are associated with vertical compaction and expansion of the aquifer system. The aquifer system primarily consists of sand and gravel aquifers (water-transmitting units) and silt and clay aquitards (water-impeding units). The aquifer system vertically deforms in response to water-level fluctuations caused by pumping water out of or injecting water into the aquifer system. Generally, compaction is associated with declining water levels (heads) and expansion with rising heads.

Land subsidence and uplift, aquifer-system compaction and expansion, and head fluctuations have a complex relation. In Las Vegas Valley, this complexity is increased because the aquifer system is alternately pumped during high demand months and artificially recharged during other months; thus, the aquifer-system skeleton undergoes seasonal cycles of compression and expansion as heads fluctuate. Reasonable estimates of aquifer-system hydraulic properties are needed to help understand the complex relation among land subsidence and uplift, vertical aquifer-system deformation, and head fluctuations. Hydraulic-property investigations in Las Vegas Valley have focused primarily on estimating properties in productive aquifer units. Few previous studies have focused on hydraulic properties of aquitard units (see Previous Investigations section). The development of a numerical model constrained by vertical aquifer-system deformation and head observations allowed aquitard properties, which are difficult to measure directly, to be estimated.

Purpose and Scope

The purpose of this report is to document the methods used to estimate hydraulic-property values that affect vertical aquifer-system deformation at the Lorenzi site and present the estimated values. Values were estimated for (1) aquitard vertical hydraulic conductivity, (2) aquitard inelastic skeletal specific storage, (3) aquitard elastic skeletal specific storage, and (4) aquifer elastic skeletal specific storage. A 1-D, finite difference, transient ground-water flow model for the period 1901–2000 was developed to simulate vertical aquifer-system deformation and nonlinear-regression methods were used to calibrate the model and refine previously estimated property values.

The 1-D model is a simplified representation of the portion of the aquifer system that is monitored by the Lorenzi site extensometer (USGS-EXT1). Estimated historic compaction and deformation measured by USGS-EXT1 do not adequately support a model that has a different set of hydraulic-property values for each aquifer-system unit. Instead, only two sets of property values are estimated, one for aquifers and one for aquitards, and the values are considered averages for the system units and not necessarily representative of any given point in the physical system. Particular attention was given to the assignment of specified heads and temporal and spatial discretization. Estimated and measured vertical aquifer-system deformation data were used for the nonlinear regression. Model results and regression statistics were analyzed to evaluate the model and estimated hydraulic-property values.



EXPLANATION

— 1 — **Subsidence contours**—Contours are in feet, interval is variable. (Modified from Bell and others, 2000)

Fault

Lorenzi site

P169 **Benchmark and name**

SNMRE **Well and name**

Figure 2. Land-subsidence contours for 1963–2000, benchmarks used to help estimate historic compaction trends, wells used to help estimate historic water-level trends, selected faults, and the Lorenzi site, Las Vegas Valley, Nevada.

Aquifer-system mechanics, numerical modeling, and parameter estimation are discussed briefly. Assumptions, data limitations, model limitations, and regression results also are discussed. This report does not focus on data and presents only the most pertinent data to the model and regression. Other data specific to this study can be found in Pavelko (2000) or requested from the Henderson, NV, office of the USGS.

Study Area

Las Vegas is in southern Nevada and the Las Vegas Valley aquifer system is in the southern part of the Great Basin Regional Aquifer System[1] (fig. 1). Las Vegas Valley is about 1,600 mi^2, with altitudes ranging from about 1,600 ft above sea level on the valley floor to about 12,000 ft above sea level in the nearby Spring Mountains. The northwest-trending valley is bounded on all sides by various mountains. The Las Vegas Wash and tributaries drain the valley runoff eastward into Lake Mead. Average annual precipitation ranges from about 4 in. on the valley floor to more than 20 in. on the surrounding mountains. Temperatures on the valley floor range from below freezing to over 115°F.

[1] Formal hydrographic areas in Nevada were delineated systematically by the U.S. Geological Survey and Nevada Division of Water Resources in the late 1960's (Cardinalli and others, 1968; Rush, 1968) for scientific and administrative purposes. The official hydrographic-area names, numbers, and geographic boundaries continue to be used in USGS scientific reports.

The Lorenzi site, established in 1994, is in northwestern Las Vegas (figs. 1 and 2) and consists of three nested piezometers (USGS-PZD, USGS-PZM, and USGS-PZS) and a vertical borehole extensometer (USGS-EXT1; table 1; Pavelko, 2000). The location, which is on the southern edge of a large subsidence bowl (Bell and others, 2000), was selected by LVVWD personnel based on site availability. The site is within 2 mi of 18 municipal wells, generally to the south and west, which pump ground water from about May through September and provide artificial recharge from about October through May. Of the 18 wells, 12 are used to pump ground water, 2 are used to artificially recharge the aquifer system, and 4 are dual-use wells used to pump and artificially recharge the aquifer system. Additional municipal wells are beyond the 2-mi radius.

History of Land Subsidence in Las Vegas Valley

Land subsidence in Las Vegas Valley is attributed mainly to compaction of the aquifer system caused by ground-water withdrawals. Maxey and Jameson (1948) first recognized land subsidence from comparisons of leveling surveys made by the U.S. Coast and Geodetic Survey and the USGS in 1915, 1935, and 1941. Since then, repeat surveys of regional networks, newly established benchmarks, local transects, and Global Positioning Satellite (GPS) sites have shown continued land

Table 1. Well-construction data for piezometers and the extensometer at the Lorenzi site, Las Vegas, Nevada

[The U.S. Geological Survey (USGS) identifies sites with a unique 15-digit number based on a latitude-longitude grid. The first six digits denote degrees, minutes, and seconds of latitude, the next seven digits denote degrees, minutes, and seconds of longitude, and the last two digits denote a unique sequence number within a 1-second grid of latitude and longitude. --, not applicable]

Well Name	USGS site identification number	Date drilled (1994)	Depth	Casing depth	Top of screened interval	Bottom of screened interval
			feet below land-surface			
USGS-PZD	361410115142601	May 18	703	697	677	687
USGS-PZM	361410115142602	May 18	703	467	447	457
USGS-PZS	361410115142603	May 18	703	320	300	310
USGS-EXT1	361410115142604	April 3	800	780	--	--

subsidence throughout large portions of the valley. The surveys, which were limited in temporal and spatial details, indicated that subsidence continued slowly into the mid-1960's after which rates began increasing through 1987 (Bell, 1981; Bell and Price, 1993). By the 1970's, damages to engineered structures had been attributed to subsidence and subsidence-related earth fissures (Mindling, 1971; Bell, 1981; Bell and Price, 1993; Bell, 1997).

Benchmark and GPS surveys and interferometric synthetic aperture radar (InSAR) data (Galloway and others, 2000) acquired for 1992–97 (Amelung and others, 1999; Bell and others, 2000 and 2002; Hoffmann and others, 2001) have delineated four localized subsidence bowls within a larger, valley-wide subsidence bowl (fig. 2). The deepest localized subsidence bowl, in the northwestern part of the valley, subsided more than 5.5 ft between 1963 and 1998 (Bell and others, 2000), in addition to nearly 1 ft of subsidence that occurred between 1935 and 1950 (Bell, 1981). The other localized bowls subsided from about 2.3 to 3.3 ft between 1963 and 1998 (Bell and others, 2000). Comparisons of land subsidence and water-level change maps show that areas of maximum subsidence do not necessarily coincide with areas of maximum head declines. One likely explanation is that areas with high subsidence rates are underlain by a larger aggregate thickness of fine-grained, compressible sediments than those areas with lower rates (Bell and Price, 1993).

Since 1988, wintertime artificial-recharge programs have mitigated land subsidence by stabilizing or raising heads on a valley-wide scale. Seasonal uplift is associated with the periods of artificial recharge, but residual compaction continues to dominate the long-term trend.

Previous Investigations

Water-resources investigations primarily on land subsidence and related issues in Las Vegas Valley are discussed by Malmberg (1964), Mindling (1965, 1971), Bell (1981), Waichler and Cochran (1991), Bell and Price (1993), Jeng (1998), Pavelko and others (1999), Pavelko (2000), Sneed and others (2000), and Pavelko (2003). Amelung and others (1999), Bell and others (2000, 2002), Hoffmann and others (2001), and Hoffmann (2003) examine land subsidence in Las Vegas Valley using InSAR data. General water-resources investigations that include information about land subsidence in Las Vegas Valley include Maxey and Jameson (1948), Domenico and others (1964), Malmberg (1965), Plume (1989), and Morgan and Dettinger (1996). In Las Vegas Valley, Domenico and others (1966) studied geologic controls of land subsidence and Harrill (1976) studied ground-water storage depletion. General hydrologic investigations of Las Vegas Valley include Carpenter (1915).

Ground-water flow, including land subsidence, in Las Vegas Valley was simulated by Morgan and Dettinger (1996) using a modified "quasi-three-dimensional" flow model (Trescott, 1975; Trescott and Larson, 1976). Past and future land subsidence were simulated for two sites in Las Vegas Valley (Waichler and Cochran, 1991) using the COMPAC model (Helm, 1974, 1975). Jeng (1998) converted the Morgan and Dettinger (1996) model to MODFLOW and simulated ground-water flow and land subsidence. Okuyan (2000) simulated past and future land subsidence and rebound for selected sites in Las Vegas Valley. Preliminary model results of the Lorenzi model were discussed in Sneed and others (2000) and Pavelko (2003).

Acknowledgments

The development of the numerical ground-water flow model and application of the compaction package were guided by Michelle Sneed, USGS, Sacramento, California. Assistance with UCODE and nonlinear-regression techniques was provided by Claire Tiedeman, USGS, Menlo Park, California. Technical and field assistance with the extensometer, information critical to this project, were provided by Frank Riley, USGS, Menlo Park, California. The Nevada Power Company allowed the Lorenzi site to be constructed and maintained at their Lorenzi substation.

HYDROGEOLOGY

Las Vegas Valley is a sediment-filled structural trough covering about 1,600 mi^2. The predominantly gravel, sand, silt, and clay sediments overlay bedrock and form the Las Vegas Valley aquifer system (fig. 3). The carbonate-rich assemblage of sediments was eroded by wind and water from surrounding bedrock highlands. Early on, these sediments were deposited on an uneven, faulted bedrock surface and then over some-

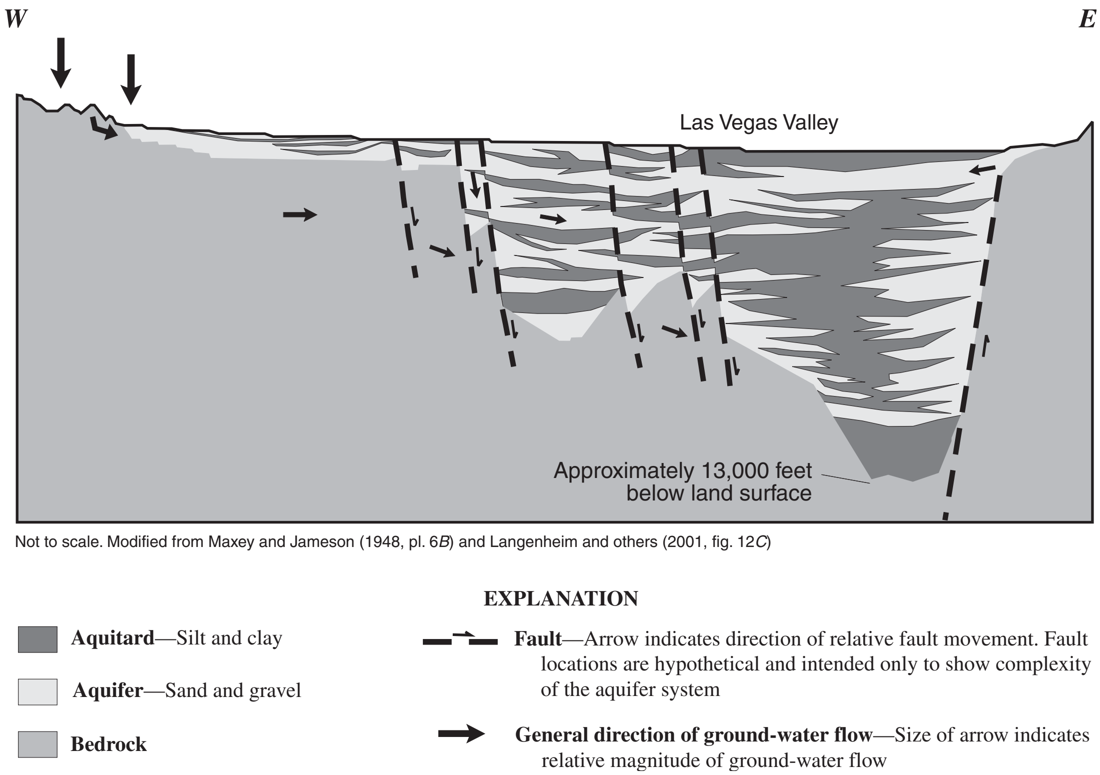


Figure 3. A simplified hydrogeologic cross section of the Las Vegas Valley aquifer system, Nevada.

what irregular surfaces shaped by previous episodes of deposition, erosion, and fault movement. Depending on intensity, runoff from rain and snow falling on the higher mountain ranges, such as the Spring Mountains bounding the valley on the west (fig. 1), transported and deposited variously sized sediment onto the valley floor. During some of the wetter times of the Quaternary Period, springs, marshes, ponds, and possibly lakes (Mifflin and Wheat, 1979; Quade and others, 1995) that covered the lower parts of the valley floor deposited sequences of fine-grained sediments.

From the Miocene through Holocene Epochs (Plume, 1989), alluvial and fluvial processes deposited a thick accumulation of interbedded and interfingered, coarse- and fine-grained sediment. Coarse-grained sand and gravel tend to rim the valley forming alluvial fans and terraces especially in the northern, western, and southern parts of the valley. The sediment assemblages generally thicken and become finer-grained toward the central and eastern part of the valley (fig. 3), where their total thickness may exceed 13,000 ft (Langenheim and others, 1998).

Precipitation runoff enters the alluvial aquifer system below the mountainous source areas and flows downgradient toward the central and eastern parts of the valley, where the depth to bedrock is greatest. At higher elevations, ground water flows through sand and gravel aquifers, but the flow is increasingly impeded and the water confined by low-permeability clay and silt aquitards that are interfingered with the aquifers downgradient.

In Las Vegas Valley, ground water generally is pumped from the upper 2,000 ft of the aquifer system. Sediments from about 200 to 2,000 ft deep generally are capable of transmitting significant quantities of ground water and have been referred to as the principal, artesian, or developed-zone aquifer (Maxey and Jameson, 1948; Malmberg, 1965; Harrill, 1976; Morgan and Dettinger, 1996). The principal aquifer has been subdivided into shallow, middle, and deep zones that are separated by aquitards. The aquifer units within the principal aquifer contain numerous thin, laterally discontinuous interbeds of low-permeability silt and clay that are interfingered in places. The principal aquifer extends from the sand and gravel deposits along the margins of the valley and becomes discontinuous and less prevalent towards the central and eastern parts of the valley, where clay and silt predominate (Plume, 1989). In places, there may be a decrease in permeability with depth for the deep zone of the principal aquifer (Maxey and Jameson, 1948). Overlying the principal aquifer, in places, is a 100- to 300-ft thick section of clay, sand, and gravel often referred to as the near-surface reservoir.

Lorenzi Site

Three thick aquifers and three thick aquitards are monitored at the Lorenzi site, as indicated by geophysical and lithologic logs from the extensometer borehole (fig. 4; Paillet and Crowder, 1996; Pavelko, 2000). Geophysical logs indicate the aquifer depths range from 255 to 308, 420 to 500, and 605 to 800 ft below land surface (F.L. Paillet, U.S. Geological Survey, written commun., 1994). The shallow aquitard (0–255 ft below land surface) likely corresponds to the near-surface reservoir and the underlying sediments to the principal aquifer (Harrill, 1976). The lithologic log indicates that the aquifers consist of sand and gravel with interbedded layers of silt and clay, and the aquitards consist mostly of silt and clay (T.J. Burbey, U.S. Geological Survey, written commun., 1994). Gravity data for Las Vegas Valley (Langenheim and Jachens, 1996, V. Langenheim, U.S. Geological Survey, written commun., 2000, and Langenheim and others, 2001) were evaluated to determine the depth of the contact between low-density (compactible) sediments and underlying higher-density (competent) sediments or rock at the Lorenzi site. Data indicate that the gravity-predicted depth occurs between 750–800 ft below land surface and is approximately equal to the depth of the extensometer (800 ft below land surface). Therefore, for purposes of this report, the depth to the base of compactible sediments at the Lorenzi site was considered to be equal to the depth of the extensometer.

MECHANICS OF VERTICAL AQUIFER-SYSTEM DEFORMATION

The aquitard-drainage model describes physical processes associated with aquifer-system head fluctuations and associated vertical deformation. [See Holzer (1998) for a history of the aquitard-drainage model.] The focus is on the slow equilibration and vertical compression, or compaction, of aquitards resulting from head declines in adjacent aquifers. The most important components of the aquitard-drainage model are encompassed in the principle of effective stress and the theory of hydrodynamic consolidation (Terzaghi, 1925, 1943). The principle of effective stress describes the relation among aquifer-system stresses that contribute to vertical deformation. Vertical deformation is dependent, in part, on the storage properties of aquifer-system units, which incorporate the compressibility, thickness, and stress history of aquifer-system units. The

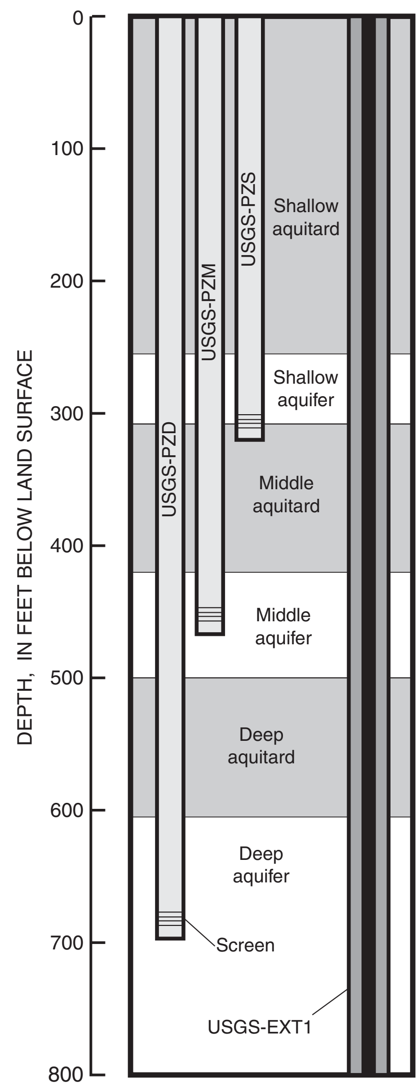


Figure 4. The generalized hydrogeology, piezometers, and extensometer at the Lorenzi site, Las Vegas, Nevada. Horizontal is not to scale.

theory of hydrodynamic consolidation explains the slow equilibration and residual compaction of aquitards in response to aquifer-head declines, and is related to the stresses, storage properties, thickness, and vertical hydraulic conductivity of aquifer-system units.

Principle of Effective Stress

Vertical aquifer-system deformation in Las Vegas Valley primarily is caused by head fluctuations that result from pumping water out of, or injecting water into, the aquifer system. The storage coefficient of aquifer-system sediments is the amount of water released from, or taken into, storage per unit area per unit decline, or rise, in hydraulic head, respectively. Water released from storage comes from the compression of the granular matrix (skeleton) of the aquifer system and expansion of water, and water taken into storage causes expansion of the skeleton and compression of water. The principle of effective stress (Terzaghi, 1925, 1943) describes the relation of fluctuating heads, expressed as equivalent changes in pore-water pressure, and vertical stresses related to aquifer-system deformation:

$$\sigma_T = p + \sigma_e, \qquad (1)$$

where σ_T is the total stress on the aquifer system (the geostatic load, or weight of overlying sediments and water), p is the pore-water pressure, and σ_e is the effective, or intergranular, stress. Thus, pore-water pressure and the aquifer-system skeleton support the weight of overlying sediments and water. For a confined aquifer system without a water-table aquifer, such as at the Lorenzi site, it can be assumed that σ_T remains constant and a change in p (head fluctuation) causes an equal and opposite change in σ_e. Changes in σ_e of an aquifer system can cause vertical aquifer-system deformation. For example, when water is pumped from the system, heads decline and p decreases, which results in an increase in σ_e; the increase in σ_e causes aquifer-system compaction to a degree dependent on the compressibility of the sediments and the previous stress history.

Aquifer-system sediments have an elastic and inelastic compressibility and, generally, the relation of the current σ_e to the past maximum effective stress, or preconsolidation stress, $\sigma_{e(max)}$, determine whether deformation will be elastic (recoverable) or inelastic (permanent). Generally, the inelastic compressibility of aquitards is 1 to 3 orders of magnitude larger than the elastic compressibility of aquitards, the elastic compressibility of aquitards is about an order of magnitude larger than of aquifers, and the inelastic compressibility of aquifers is considered negligible. Provided that σ_e remains below $\sigma_{e(max)}$, aquifer-system deformation will be elastic. If $\sigma_{e(max)}$ is exceeded, usually a result of heads declining below the past minimum head, deformation will be inelastic.

The compressibilities of aquifer-system sediments are termed skeletal compressibilities and often are expressed in terms of skeletal specific storages:

$$S_{sk} = S_{ske} = \alpha_{ke}\rho g, \qquad \text{for } \sigma_e \le \sigma_{e(max)}, \qquad (2)$$

$$S_{sk} = S_{skv} = \alpha_{kv}\rho g = 0, \text{ for } \sigma_e > \sigma_{e(max)}, \qquad (3)$$

$$S'_{sk} = S'_{ske} = \alpha'_{ke}\rho g, \qquad \text{for } \sigma_e \le \sigma_{e(max)}, \text{ and} \qquad (4)$$

$$S'_{sk} = S'_{skv} = \alpha'_{kv}\rho g, \qquad \text{for } \sigma_e > \sigma_{e(max)}, \qquad (5)$$

where S_{sk} is the skeletal specific storage, α_k is the skeletal compressibility, subscripts e and v denote elastic and inelastic properties, respectively, ρ is the water density, g is gravitational acceleration, and primes denote aquitard properties. Expressed as an equivalent head, $\sigma_{e(max)}$ is called the preconsolidation head; when heads are above the preconsolidation head, deformation is elastic and when heads are below the preconsolidation head, deformation is inelastic.

The compressibility of water, β_w, also can be expressed as a specific storage:

$$S_{sw} = \beta_w \rho g, \qquad (6)$$

where S_{sw} is the specific storage of water. In the inelastic range of stress experienced by most developed aquifer systems, S_{sw} is considered negligible, but may be a significant component in the elastic range of stress. The specific storage of an aquifer-system unit is the sum of the skeletal specific storage and the specific storage of water. The skeletal storage coefficient of an aquifer-system unit is the product of that unit's skeletal specific storage and thickness.

Theory of Hydrodynamic Consolidation

The theory of hydrodynamic consolidation (Terzaghi, 1925, 1943) describes the delay involved in aquitard equilibration when heads are lowered in adjacent aquifers and the associated compaction that continues afterwards. At the onset of pumping, most water derived from aquifer systems is withdrawn from aquifers. Because aquitards have a much lower permeability than aquifers, the equilibration and drainage of aquitards may proceed slowly, and heads in aquitards may lag far behind the changing heads in adjacent pumped aquifers. In aquifer systems that have thick aquitards and undergo seasonal pumping, such as at the Lorenzi site, aquitard heads often do not equilibrate with pumped aquifers before the next season of pumping begins, thus aquitards are continuously equilibrating to the effects of past pumping. In thick aquitards, the slow drainage and release of water from storage is accompanied by the migration of an increased σ_e towards the inner portions of the aquitard. If the internal stresses exceed $\sigma_{e(max)}$, the slow drainage is accompanied by inelastic compaction.

Residual compaction is the inelastic aquitard compaction that would occur because of an increase in effective stress, but has not yet occurred because aquitard heads have not equilibrated to heads in adjacent aquifers and are still draining and compacting (Poland and others, 1972). The slow drainage and equilibration of the aquitards, as described above, can result in decades or more of residual compaction for aquifer systems with thick aquitards and large head declines (Ireland and others, 1984). The time constant of an aquitard describes how long a doubly draining aquitard will take to achieve about 93 percent of the total possible compaction for a given head decline (Riley, 1969). A doubly draining aquitard is an aquitard between two aquifers with identical heads that are lower than heads in the aquitard and, therefore, the aquitard releases water into the overlying and underlying aquifers. The time constant (τ) is expressed as:

$$\tau = \frac{S'_{skv}(b'/2)^2}{K'_v}, \tag{7}$$

where S'_{skv} is aquitard inelastic skeletal specific storage, b' is the thickness of the aquitard, and K'_v is aquitard vertical hydraulic conductivity. For aquitards with only one adjacent aquifer, a directly comparable τ cannot be made but can be estimated by replacing $b'/2$ with b' (Epstein, 1987).

NUMERICAL MODEL

A numerical model of the Lorenzi site was developed to simulate vertical aquifer-system deformation and estimate aquitard vertical hydraulic conductivity (K'_v), aquitard inelastic and elastic skeletal specific storage, S'_{skv} and S'_{ske}, respectively, and aquifer elastic skeletal specific storage (S_{ske}). The estimated hydraulic-property values are considered average values for the composite thickness of aquifer-system unit types. A conceptual model was developed using geophysical, lithologic, head, and vertical-deformation data collected at the site. MODFLOW-96 (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996), a modular finite-difference ground-water flow model, was used to develop the 1-D, vertical numerical model of the Lorenzi site conceptual model. The Flow and Head Boundary (FHB1) package was used to specify heads at selected times and depths (Leake and Lilly, 1997). The Interbed-Storage (IBS1) package was used to simulate deformation (Leake and Prudic, 1991). The Block-Centered Flow package was used to simulate transient ground-water flow and the Strongly Implicit Procedure package was used to solve a set of simplified ground-water flow equations (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). The ground-water flow equations were solved iteratively to compute heads in each cell for each time step. For each iteration, calculated heads were compared to heads from the previous iteration until the head differences between iterations were less than 0.0001 ft.

Conceptual Model

The conceptual model of the Lorenzi aquifer system is a simplified and qualitative physical description of the geometry and processes of the aquifer system and was developed using geophysical logs (F.L. Paillet, U.S. Geological Survey, written commun., 1994), lithologic logs (T.J. Burbey, U.S. Geological Survey, written commun., 1994), and head and vertical-deformation data collected at the Lorenzi site.

The conceptual model consists of three aquifers and three aquitards constituting a total thickness of 735 ft, from 65 to 800 ft below land surface (fig. 5). The uppermost 65 ft of sediment were not included in the model because that depth interval likely is unsaturated and, therefore, not subject to compaction. The aquifers and aquitards are assumed to have homogeneous and isotropic hydraulic properties, and each unit type is assumed to have an identical set of hydraulic-property values. Heads and ground-water flow in aquifers are considered to be controlled entirely by pumpage and artificial recharge, and heads and flow in aquitards are controlled entirely by aquifer heads. Aquifer hydraulic conductivity is sufficiently high that aquifers equilibrate instantaneously throughout their thickness to head changes. However, aquitard conductivity is sufficiently low that large, nonlinear, vertical-head gradients form within each aquitard unit as heads in

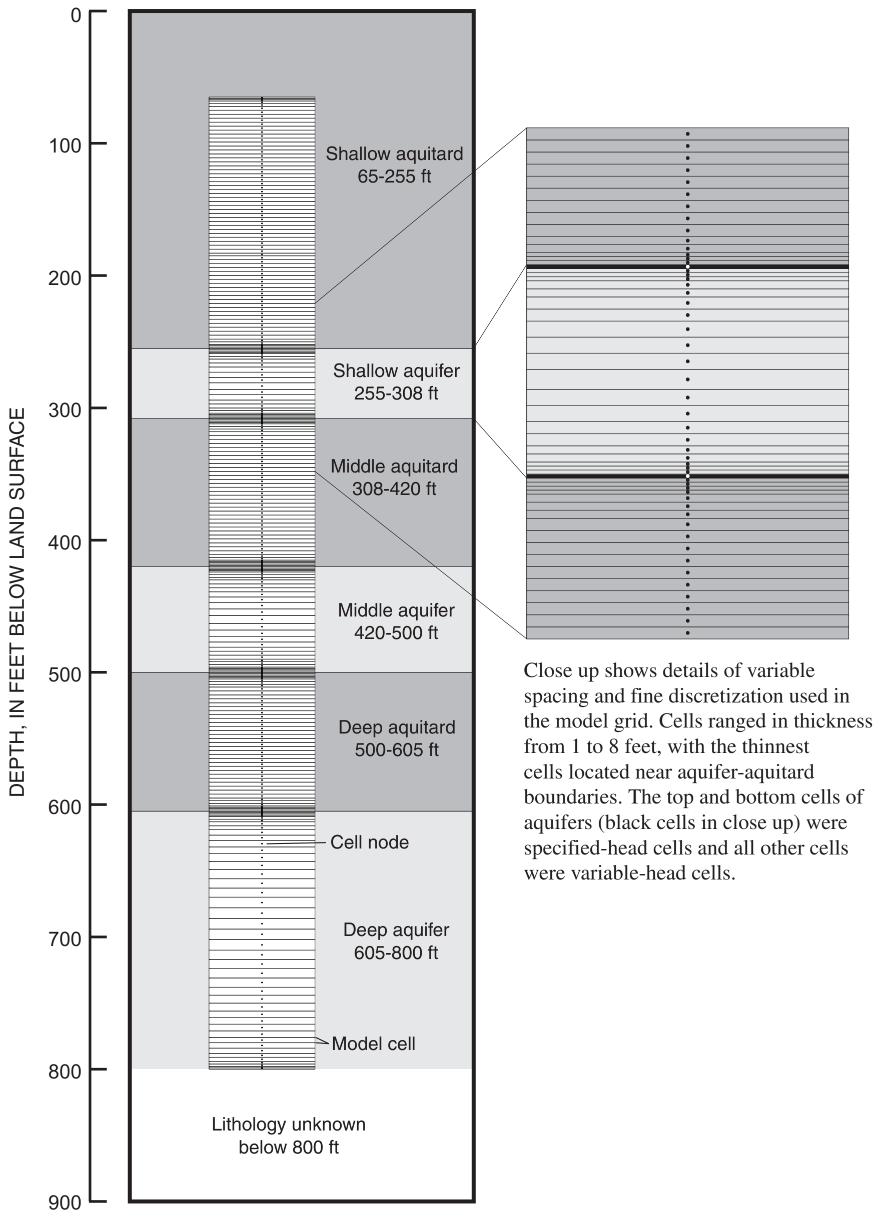


Figure 5. The generalized hydrogeology of the conceptual model and model grid, including a close-up of the model grid showing variable cell spacing, for the Lorenzi model, Las Vegas, Nevada.

adjacent aquifers change. For the purposes of the 1-D model, head fluctuations and aquifer-system deformation account for all storage changes—no ground water is assumed to flow into or out of the system.

All aquifer-system deformation in the conceptual model is assumed vertical and a result of head fluctuations. Generally, compaction occurs when heads decline and expansion occurs when heads rise. Deformation occurs as elastic compaction and expansion in aquifers and aquitards and inelastic compaction in aquitards—inelastic compaction does not occur in aquifers. The majority of elastic deformation occurs in aquifers and inelastic deformation occurs only when aquitard heads are below their preconsolidation head. Residual compaction occurs only in aquitards and when all or portions of the aquitard have heads below their preconsolidation head. Because the middle and deep aquitards (fig. 5) are doubly draining and the shallow aquitard only drains downward, the assumption is made that the shallow aquitard equilibrates and therefore compacts much more slowly than the other aquitards.

A conceptual history of heads at the Lorenzi site was developed to guide the transient progression of the numerical model. From about 1901 to 1915, the system was in steady-state equilibrium (Carpenter, 1915; Maxey and Jameson, 1948; Malmberg, 1965) with higher heads in lower units and naturally occurring seasonal fluctuations. Beginning around 1915, ground-water pumpage caused heads to decline and they declined until about 1992, although from about 1940 to 1992 they declined much more rapidly than from 1915 to 1940. Since about 1950, seasonal pumpage has amplified annual cycles of head fluctuations. Also around 1950, increased pumpage in deeper units caused the distribution of aquifer heads to reverse such that the shallow units had higher heads. By 1992, estimated heads had declined by as much as 320 ft in the deep and middle aquifers and 250 ft in the shallow aquifer. Large, nonlinear, vertical-head gradients formed in the aquitards during this time (fig. 6) because their low vertical hydraulic conductivity prohibited water from equilibrating as quickly as the declining aquifer heads, and new preconsolidation heads were established in the aquifers. Since 1992, heads around the Lorenzi site have been rising because artificial recharge has increased. After 1992, as aquifer heads generally were rising and aquitard heads continued to equilibrate (decline) with aquifers, nonlinear head gradients between adjacent aquifers and aquitards decreased.

The equilibration of the relatively high aquitard heads to the lower aquifer heads caused inelastic residual compaction to occur in the aquitards. From 1988 to 1996, during seasons of artificial recharge and rising aquifer heads, the rates of aquitard residual compaction were higher than rates of aquifer expansion, such that aquifer expansion was masked entirely. Since 1997, the rate of aquifer expansion during periods of artificial recharge exceeded the rate of aquitard residual compaction (Pavelko, 2000).

Discretization

Although the conceptual model was developed as a 1-D vertical model, the numerical model was spatially discretized into a 1-D horizontal model to take advantage of the layer-wise formatting of MODFLOW-96 data arrays. Thus, a 1-ft wide vertical column of the conceptual aquifer system (fig. 5) was represented by a 1-ft tall numerical layer and the 735-ft thickness of the aquifer system was represented by a single row of 250 numerical columns that varied in width in the row-wise dimension. To accommodate the column-to-layer translation, the assignment of hydraulic properties in the model needed to be modified. Hydraulic properties that describe vertical flow were assigned to data arrays typically reserved for horizontal properties. For example, vertical hydraulic-conductivity values were assigned using the transmissivity data array. The translation modification, described in the IBS1 documentation (Leake and Prudic, 1991), also was used to simulate 1-D, vertical, aquifer-system deformation in Antelope Valley, California (Sneed and Galloway, 2000). This report, and the figures and tables within, refers to model columns as layers to maintain the terminology and geometry of the conceptual aquifer system.

Spatially, there were 250 model layers (fig 5). The three aquifers were represented by 93 layers, which ranged in thickness from 1 to 8 ft, for a total of 328 ft. The three aquitards were represented by 157 layers, which ranged in thickness from 1 to 3 ft, for a total of 407 ft. The model was finely discretized into thin layers to minimize a limitation of the IBS1 package in simulating residual compaction (see Model and Regression Limitations section). The resultant model

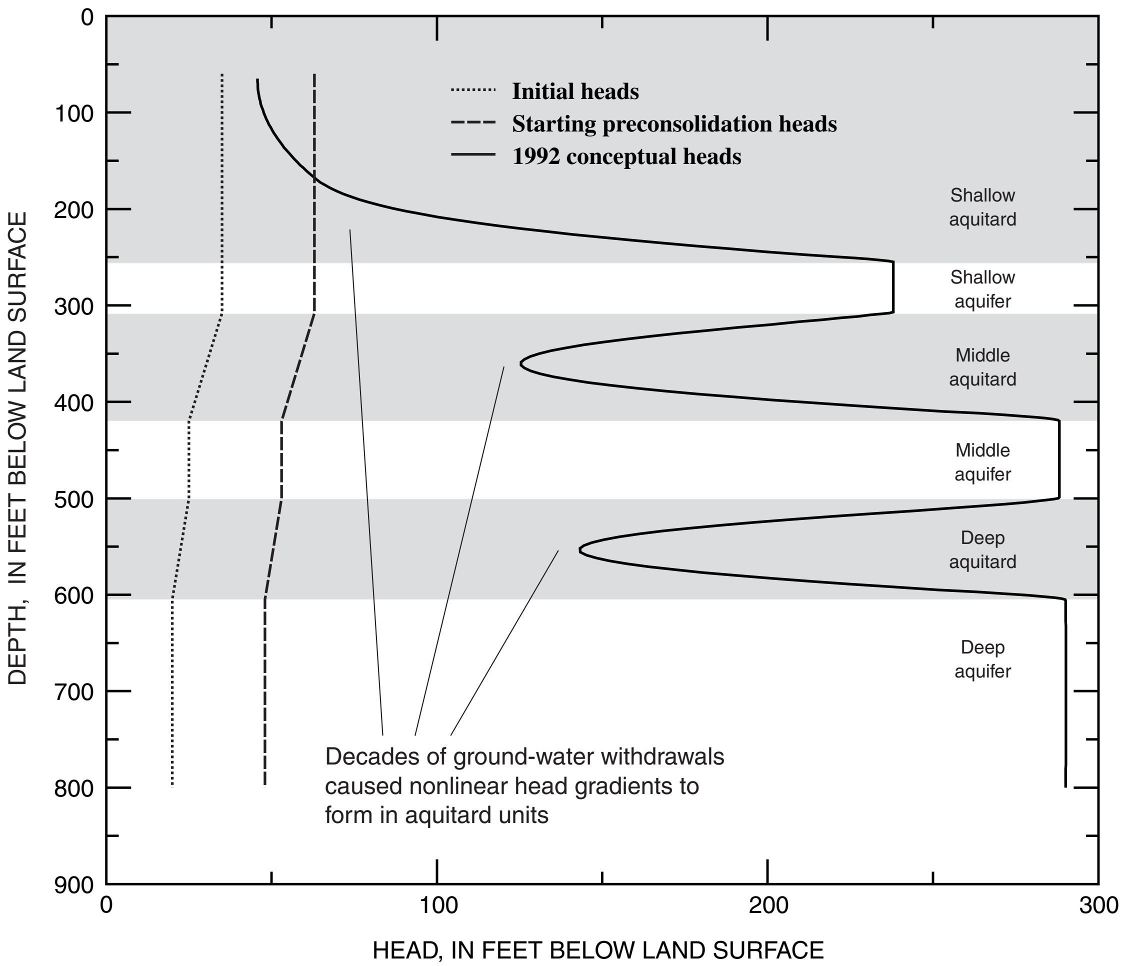


Figure 6. The initial, starting preconsolidation, and 1992 conceptual heads for the Lorenzi model, Las Vegas, Nevada.

grid generally had thicker layers for aquifers than for aquitards and the thinnest layers were near aquifer-aquitard boundaries (fig. 5).

The model simulated deformation from January 1, 1901, to November 19, 2000. The historic period, 1901 through 1994, was simulated using ninety-four 1-year (365.25 days) stress periods, each with twelve 1-month (30.4375 days) time steps. The recent period, 1995–2000, was simulated using forty-three 50-day stress periods, each with four-hundred 3-hour time steps. The historic period of the model established the hydrologic conditions for the recent period, including preconsolidation heads and aquitard-head distributions, which were important for simulating recent-period deformation. The temporal discretization of the recent period was finer than the historic period to facilitate use of the high measurement frequency and more accurate data from the Lorenzi site. The shorter time steps also provided for a better evaluation of simulated seasonal and shorter-term deformation.

Boundary Conditions

The simplified hydrologic processes of the conceptual model were implemented into a numerical model, in part, by designating boundary conditions to appropriate model cells. The top and bottom cells of each aquifer unit were designated as specified-head cells, in which estimated or measured heads were assigned at specified model times using the FHB1 package (Leake and Lilly, 1997). All other model cells were designated as variable-head cells (fig. 5), which allowed heads to fluctuate according to heads in adjacent cells. By default, the lateral, upper, and lower boundaries of the vertical column (fig. 5) are no-flow boundaries and, therefore, only vertical flow is simulated and no water can enter or exit the system, except as specified-head changes.

Initial Head and Compaction Conditions

Initial conditions described the conceptual steady state of the predevelopment aquifer system in 1901. Initial conditions were assigned to each cell with initial-head, preconsolidation-head, and starting-compaction data. Initial aquifer heads (fig. 6) were based primarily on Carpenter (1915) and adjusted during model calibration. Carpenter suggests that a 274-ft deep, unnamed well approximately 1 mi from the future Lorenzi site had a head of 2,279 ft above sea level. Thus, assuming a relatively flat head gradient, the head in USGS-PZS, a 305-ft deep well, would have about the same water-level altitude as the unnamed well, which would equate to a head of approximately 30 ft below land surface. During calibration, initial heads for USGS-PZS were varied from 0 to 70 ft below land surface, and the relation of shallow to middle and deep aquifer heads were adjusted to find the best combination to simulate historic data. Initial-head values of 35, 25, and 20 ft below land surface were chosen for the shallow, middle, and deep aquifers, respectively. Initial aquitard heads were linearly interpolated between estimated heads in adjacent aquifers under the assumption that the system was in equilibrium. Initial preconsolidation heads (fig. 6) for aquifers were estimated by comparing historical trends of land subsidence and heads to determine what the approximate heads were in about 1935, when land-subsidence rates began to significantly increase. Similar to initial aquitard-head distributions, preconsolidation heads for aquitards were linearly interpolated between heads in adjacent aquifers under the assumption that the top and bottom fringes of the aquitards were in equilibrium with the bounding aquifers when subsidence began. Based on available historic data, the starting compaction was assumed zero.

Transient Progression

The FHB1 package (Leake and Lilly, 1997) was used to assign heads to cells designated as specified-head cells (fig. 5). From 1901 to 1950, one head per year; from 1950 to 1995, three heads per year; and from 1995 to 2000, one head per day were specified. FHB1 linearly interpolated heads for specified-head cells for model time steps that were not assigned specified heads.

Specified heads for the historic period were estimated for each aquifer (fig. 7*A*). Heads from 1901 to 1942 were based on water-use trends and head contour maps (Maxey and Jameson, 1948; Domenico and others, 1964), because limited head data exist for wells near the Lorenzi site. From 1943 to 1994, trends for Lorenzi heads were estimated from water-use trends and heads measured in the P.J. Goumond well (fig. 1). Heads measured in the SNMRE well (fig. 1) from 1971 to 1994 also were used to estimate historic-period heads for the Lorenzi site. Additionally, the estimated hydrographs incorporated historic valley-wide head trends and, finally, consideration was given to head trends measured at the Lorenzi site. Before the late 1940's, vertical ground-water flow was upward because heads in the shallow aquifer were lower than heads in the middle aquifer, which had lower heads than the deep aquifer. Between the late 1940's and early 1960's, ground-water development in the deeper units caused heads at the Lorenzi site and vicinity to lower in the middle and deep aquifers and ground water began to flow downward (Domenico and others, 1964; Harrill, 1976). The reversal, in which the vertical flow of water changes from upward to downward, was a result of pumping deeper aquifers and increasing secondary recharge to shallow aquifers.

Heads for the recent period (1995–2000; fig. 7*B*) were daily mean heads from the Lorenzi site. During periods of daily pumpage, heads fluctuated as much as 20 ft/d and, conceptually, those fluctuations caused daily fluctuations in deformation rates. However, the limited accuracy and efficiency of the extensometer prohibited those relatively quick, head-fluctuation induced, deformation-rate changes from being measured. When measured heads were used in the model, deformation-rate fluctuations were simulated and large errors resulted. For this reason, daily mean heads in wells USGS-PZD, USGS-PZM, and USGS-PZS were assigned to the specified-head cells of the deep, middle,

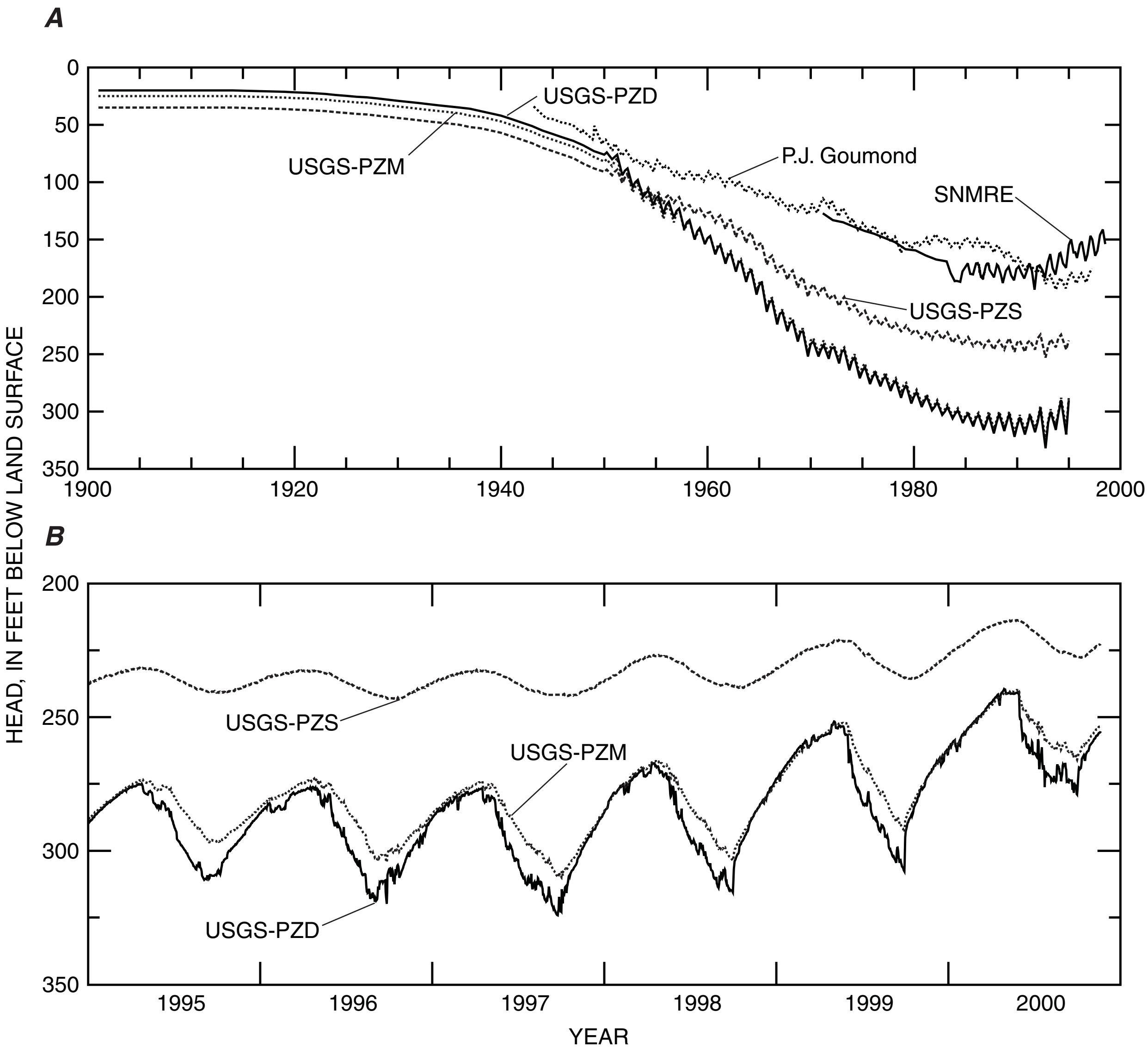


Figure 7. Hydrographs showing (*A*) heads for P.J. Goumond and SNMRE wells, used to estimate historic specified heads, and historic specified heads used in the Lorenzi model and (*B*) daily average heads for USGS-PZS, USGS-PZM, and USGS-PZD, used as recent specified heads in the Lorenzi model, Las Vegas, Nevada.

and shallow aquifers, respectively. For periods of missing data, hourly heads were estimated based on data from other Lorenzi wells or were linearly interpolated between existing data, then averaged to obtain daily means.

Aquifer-system compaction and uplift were simulated using the IBS1 package (Leake and Prudic, 1991). The IBS1 package (1) assigns, tracks, and changes preconsolidation heads according to simulated head changes; (2) assigns elastic and inelastic skeletal-storage values to cells, dependent upon the relation between current heads and preconsolidation heads; and (3) tracks vertical deformation for each cell. MODFLOW-96 accounted for changes in ground-water storage attributable to the compression and expansion of water; the IBS1 package accounted for changes in storage attributable to the compaction and expansion of the aquifer-system skeleton and computed the deformation.

Simulated ground-water flow in the Lorenzi model was driven entirely by the specified heads (fig. 7) assigned to aquifer cells and deformation was driven by the simulated flow between aquifers and aquitards. Aquitard heads fluctuated in response to changes in heads that were specified in the aquifers. When the head in a cell was higher than the preconsolidation head, the elastic skeletal storage coefficient was used to calculate deformation. When the head in a cell declined below the preconsolidation head, the inelastic skeletal storage coefficient was used to compute compaction and the preconsolidation head was reset to the new, lower head.

Hydraulic Properties

Aquifer vertical hydraulic conductivity and inelastic skeletal specific storage were not estimated by regression because the conceptual model dictated that they be constrained. Model cells representing aquifers were assigned the relatively large constant value of 0.1 ft/d for aquifer vertical hydraulic conductivity to ensure that head gradients could not form between model time steps, in accordance with the conceptual model. Model cells representing aquifers were assigned a constant value of 0 ft^{-1} for aquifer inelastic skeletal specific storage to ensure that no inelastic compaction in aquifers occurred, in accordance with the conceptual model. Aquitard vertical hydraulic conductivity (K'_v), aquitard inelastic skeletal specific storage (S'_{skv}), aquitard elastic skeletal specific storage (S'_{ske}), and aquifer elastic skeletal specific storage (S_{ske}) were estimated during model calibration by regression. Reasonable ranges for the estimated hydraulic properties were based on past studies of Las Vegas Valley and other alluvial basins in the southwestern United States because of their similar hydrogeologic settings (see Previous Investigations section). Data collected at the Lorenzi site also were used to estimate specific-storage values. Reasonable ranges of estimated properties were not used as model input, but rather were compared to regression-derived estimates to assist in determining if the regression-derived values were realistic.

The reasonable range for K'_v was 2 x 10^{-6} to 7 x 10^{-3} ft/d. Waichler and Cochran (1991) obtained estimates that ranged from 2 x 10^{-6} to 4 x 10^{-5} ft/d, by using the numerical model COMPAC (Helm, 1974, 1975) to simulate vertical aquifer-system deformation for two sites in Las Vegas. An estimated K'_v value of 8 x 10^{-6} ft/d was based on stress-deformation analyses of aquifer systems in central California (Riley, 1969). Sneed and Galloway (2000) estimated values for K'_v that ranged from 1 x 10^{-5} to 2 x 10^{-5} ft/d by using the numerical model MODFLOW-96 (Harbaugh and McDonald, 1996) to simulate vertical aquifer-system deformation for an extensometer borehole in Antelope Valley, California. Harrill (1976) estimated values for K'_v that ranged from 7 x 10^{-4} to 7 x 10^{-3} ft/d for Las Vegas Valley and less than 1 x 10^{-3} ft/d for the area around the Lorenzi site, based on vertical hydraulic gradients, thickness of aquitards, and the distribution of evapotranspiration.

The reasonable range for S'_{skv} was 7 x 10^{-6} to 1 x 10^{-3} ft^{-1}. Hanson (1989) estimated values for S'_{skv} that ranged from 7 x 10^{-6} to 3 x 10^{-4} ft^{-1} by using the numerical model COMPAC (Helm, 1974, 1975) to simulate vertical deformation for extensometers in Tucson Basin and Avra Valley, Arizona. Morgan and Dettinger (1996) estimated values for S'_{skv} that ranged from 6 x 10^{-5} to 1 x 10^{-4} ft^{-1} by using the numerical model MODFLOW-88 (McDonald and Harbaugh, 1988) to simulate ground-water flow in Las Vegas Valley, Nevada. Sneed and Galloway (2000) used the numerical model MODFLOW-96 (Harbaugh and McDonald, 1996) to simulate vertical aquifer-system deformation for an extensometer borehole in Antelope Valley, California, and estimated values for S'_{skv} that ranged from 4 x 10^{-5} to 4 x 10^{-4} ft^{-1}. Harrill (1976) estimated values for S'_{skv} that ranged from 1 x 10^{-4} to 1 x 10^{-3} ft^{-1} for Las Vegas Valley, based on land subsidence measurements, head declines, and the approximate thickness of aquitards.

The reasonable ranges for S'_{ske} and S_{ske} were based on Hanson (1989). Hanson estimated values of S'_{ske} that ranged from 1 x 10^{-6} to 2 x 10^{-5} ft^{-1} and values of S_{ske} that ranged from 3 x 10^{-8} to 2 x 10^{-6} ft^{-1}, by using the numerical model COMPAC (Helm, 1974, 1975) to simulate vertical aquifer-system deformation for extensometers in Tucson Basin and Avra Valley, Arizona.

Stress-deformation analyses (Riley, 1969) of USGS-PZD and USGS-EXT1 data were applied to refine literature-derived storage estimates. The estimated values, however, did not fall within the reasonable ranges of estimates of past studies. The stress-deformation derived estimates ranged from 2 x 10^{-7} to 2 x 10^{-6} ft^{-1} for the elastic skeletal specific storage of the aquifer system (a property that comprises both aquifer and aquitard storage) and from 6 x 10^{-7} to 1 x 10^{-6} ft^{-1} for S'_{skv}.

The discrepancies were possibly because of seasonal data trends and daily anomalies. Results from stress-deformation analyses are best when seasonal-head cycles have declining annual peaks with corresponding cycles of compaction and expansion and when residual compaction is minimal. At the Lorenzi site, however, for 1995–97 USGS-PZD had declining annual peaks without cycles of compaction and expansion, and for 1998–2000, USGS-PZD had rising annual peaks (fig. 8; Pavelko, 2000). Additionally, during summer months the extensometer record was contaminated by thermal effects on the extensometer (Pavelko, 2000) caused by daily air-temperature fluctuations of as much as 55°F in the extensometer shed. The daily thermal effects on the extensometer were recorded as vertical deformation fluctuations contrary to the conceptual model: daily head declines were associated with aquifer-system expansion and daily head recovery with aquifer-system compaction (fig. 9). Barometric pressure and borehole-air temperature did not affect extensometer data (Pavelko, 2000) or the stress-deformation analyses.

MODEL CALIBRATION

The numerical model was calibrated with a combination of trial-and-error and nonlinear-regression methods. Before and concurrent with the regression, the numerical model, including hydraulic-property values, was manually changed by trial-and-error methods until the model fit and regression statistics indicated that the physical system was sufficiently represented and simulated data were reasonable. Nonlinear regression was performed by UCODE, a computer code for universal inverse modeling (Poeter and Hill, 1998). During regression, selected parameter values, in this case hydraulic properties, were adjusted to minimize differences between simulated and observed data to obtain optimal parameter estimates. The observed data were historical compaction estimates and recent extensometer measurements. The calibrated model and estimated parameter values were evaluated by examining the water budget of the numerical model, analyzing the sensitivity of observed data to the

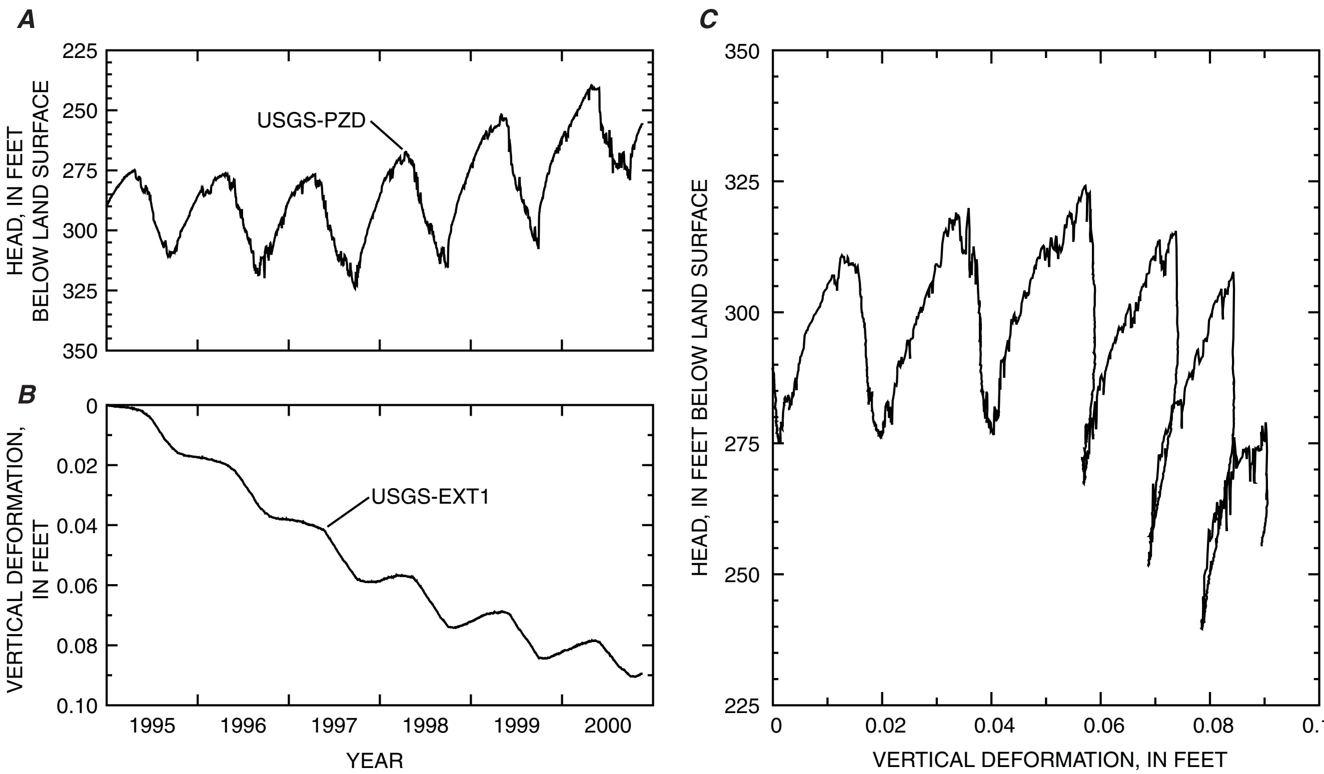


Figure 8. Graphs showing (*A*) Daily average water levels from USGS-PZD, (*B*) daily deformation from USGS-EXT1, and (*C*) stress-deformation data from USGS-PZD and USGS-EXT1, Lorenzi site, Las Vegas, Nevada.

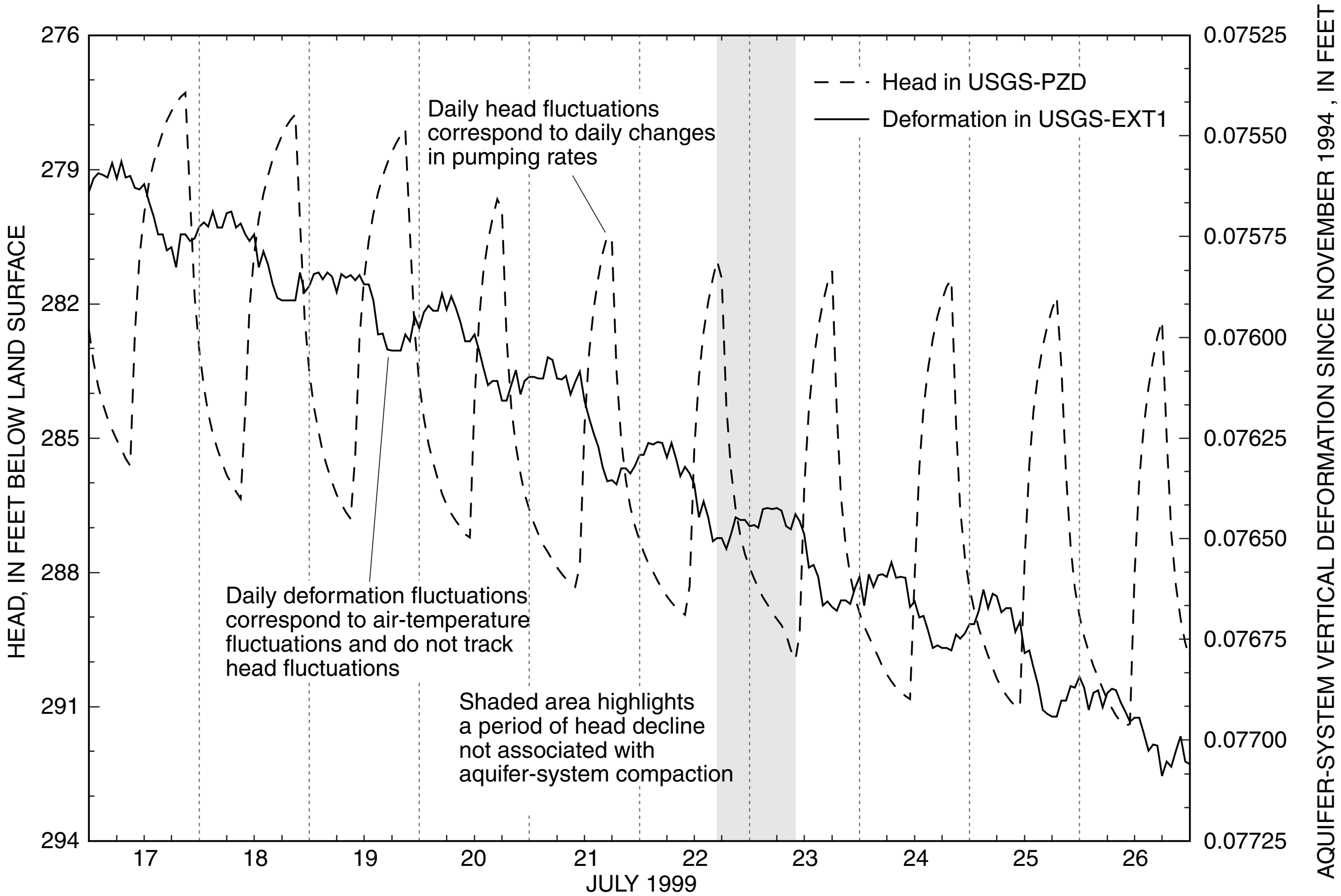


Figure 9. USGS-PZD water levels and USGS-EXT1 deformation for July 17–26, 1999, a period of diurnal pumping with an extensometer record contaminated by thermal effects, Lorenzi site, Las Vegas, Nevada.

estimated parameters, comparing simulated vertical deformation to observed data, examining simulated aquitard heads, and examining regression statistics.

UCODE iteratively ran the numerical model and systematically adjusted parameter values for each model run. The results of each model run were evaluated by UCODE to identify the run with the smallest objective function, which, statistically, is the run with the set of optimal parameter-value estimates. The weighted least-squares objective function (S) used in UCODE is defined as:

$$S = \sum_{i=1}^{n} w_i[y_i - y'_i]^2 , \qquad (8)$$

where n is the total number of observations; w_i is the weight of the ith observation; y_i is the ith observation; y'_i is the ith simulated value; and $y_i - y'_i$ is the residual for the ith observation and a measure of the model fit to y_i. Observation weights were assigned to reflect the estimated accuracy of the observations. Observation weights were derived by trial-and-error methods during the regression process. A modified Gauss-Newton method (Cooley and Naff, 1990; Hill, 1992, 1998) was used by UCODE to minimize the objective function.

No aquitard-head data were available to use as observations, which meant that the objective function was minimized based only on deformation-data errors but allowed for simulated aquitard heads that did not conform to the conceptual model and unreasonable estimated-parameter values. Regression-statistics analyses were complicated further by statistics from model runs with different weighting schemes, because subjective weight data influenced the statistics as much as quantitative simulated data. For example, a run with small weights and a poor fit, and a run with large weights and a good fit could have similar objective functions. To account for these complications, acceptable model runs were chosen based on regression statistics, qualitative analyses of simulated aquitard heads, and whether the estimated parameter values were reasonable.

As a result of head changes, the volume of water in a cell could have changed from compression or expansion of water, or compression or expansion of the skeletal matrix, or both. At the end of each stress period, a cumulative volumetric budget was calculated that detailed the volume of water that flowed into or out of each source. The budget calculations were independent of the flow-equation solution process, and therefore provided independent evidence for a valid solution (McDonald and Harbaugh, 1988). For the Lorenzi model, cumulative volumetric discrepancies at the end of each stress period were less than 0.05 percent of the total volume of water exchanged, which indicates an acceptable solution to the ground-water flow equations in the numerical model.

Observation Data

Simulated data were compared to observation data to evaluate model fit during calibration. Observation data typically were chosen because they provided important information about the parameters being estimated by regression. UCODE determined the set of parameter values associated with the minimized objective function. Weights were assigned to observation data to reflect their accuracy and importance to the regression. Observation data used for the Lorenzi model were either estimated or measured deformation data. Historic observations were based on land subsidence measurements and estimates. Recent studies support using land-subsidence data as compaction estimates for the Lorenzi site. For example, Langenheim and Jachens (1996) and Langenheim and others (2001) used gravity (V. Langenheim, U.S. Geological Survey, written commun., 2000) and borehole-lithologic data to estimate the thickness of basin fill. These studies indicate that there are about 800 ft of low-density (compactible) sediments at the Lorenzi site, the base of which corresponds to the bottom depth of the USGS extensometer. Another study (Hoffmann and others, 2001) compared annual trends of land subsidence measured with InSAR to aquifer-system compaction measured by the extensometer and the values are similar.

Historic observations consisted of 21 compaction estimates derived from benchmark surveys and InSAR data (fig. 10). Contour maps and cross sections based on data from repeat surveys between 1935 and 1987 (Malmberg, 1965; Mindling, 1971; Harrill, 1976; Bell, 1981; Bell and Price, 1993) outlined valley-wide subsidence trends based on altitude changes of benchmarks. InSAR data collected between 1992 and 1997 showed that the distribution of land subsidence in Las Vegas Valley is controlled, to a large degree, by faults (fig. 2; Amelung and others, 1999) and, thus, indicated that the benchmark data from past studies were contoured erroneously. Bell and others (2000) used benchmark data and InSAR-derived subsidence patterns to revise a contoured land subsidence map for 1963–98 (fig. 2). The new map indicated that much less subsidence occurred at the Lorenzi site than previously estimated. Consequently, historic subsidence observations were derived from historic trends delineated in past studies, current trends measured at the Lorenzi site, and recent trends and patterns measured with InSAR. Figure 10 shows land-subsidence data for benchmarks K169, P169, Q365, and V170, an estimate of subsidence for the Lorenzi site based on InSAR (Bell and others, 2000, fig. 4), and historic observations for the Lorenzi model; figure 2 shows the locations of the benchmarks.

Compaction estimates for 1901–63 were based on ranges of land subsidence measured by benchmark surveys, trends of head declines, and the trend of subsidence extrapolated from the subsidence contour map from Bell and others (2000, fig. 4). Values for 1963–87 were based largely on the Bell and others (2000, fig. 4) contour map for 1963–98, but trends of head declines, trends of historical subsidence from benchmark surveys, and recent trends of deformation measured at the Lorenzi site were considered. The trend of estimated compaction for 1989–94 was based on the trend of extensometer data and was estimated by extrapolating from the 1987 observation value.

Based on limited water-use data, no subsidence before 1901 and 0.01 ft by 1935 was assumed. Surveys in 1935 and 1941 indicated that 0.01–0.04 ft of land subsidence occurred at the Lorenzi site (Malmberg, 1965; Mindling, 1971). Surveys indicated that by 1950 0.1–0.3 ft of subsidence occurred and by 1963 0.2–0.6 ft occurred (Malmberg, 1965; Mindling, 1971). By

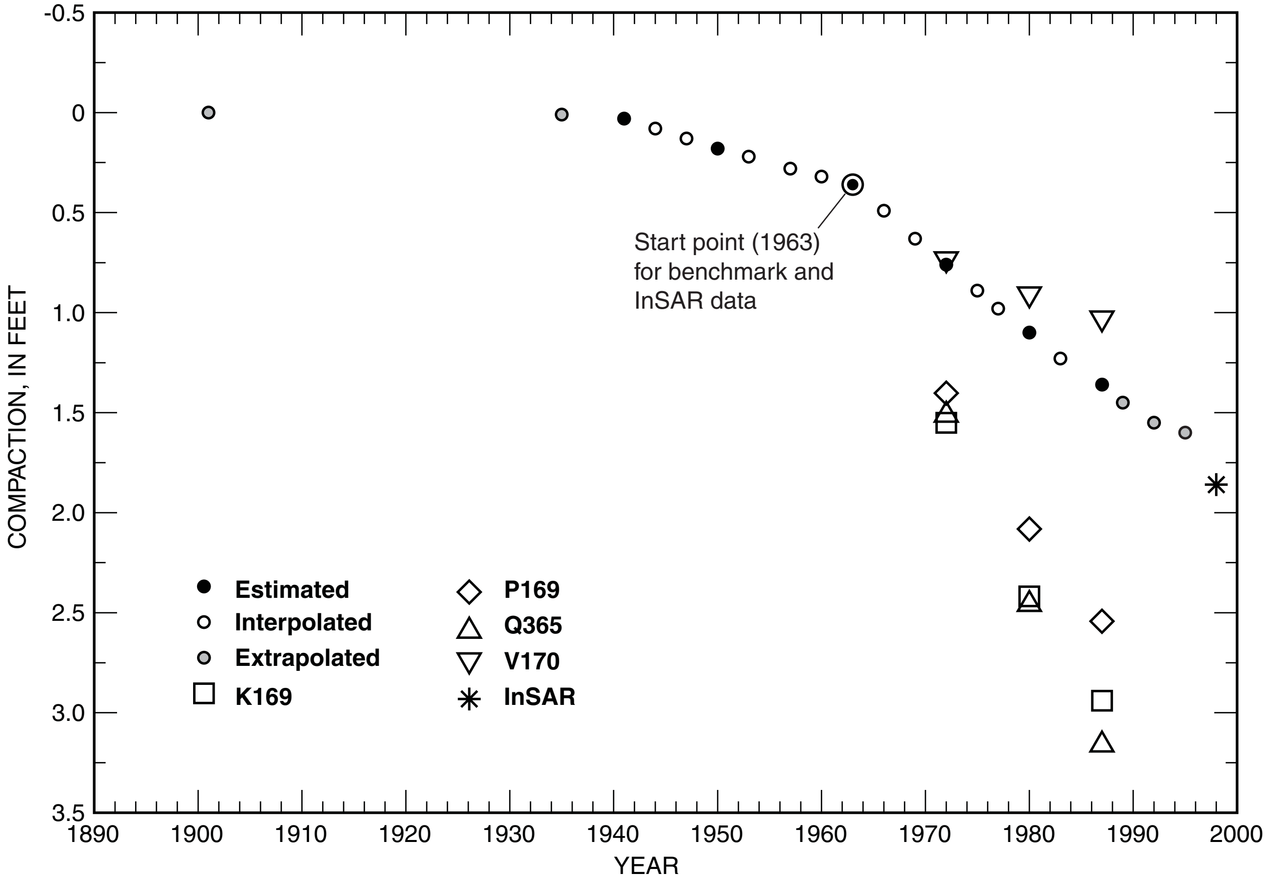


Figure 10. Estimated, interpolated, and extrapolated compaction data used as historic observations in the Lorenzi model (1901–95), compaction measured at selected benchmarks, relative to 1963, and an InSAR-derived compaction estimate (1963–98), Las Vegas, Nevada.

1972 an additional 1 ft of subsidence occurred (Harrill, 1976), from 1963 to 1980 about 1.6 ft was measured (Bell, 1981), and from 1963 to 1987 about 2.25 ft was measured (Bell and Price, 1993). These estimated ranges of subsidence were used to determine historic-period compaction observations.

Extensometer data were smoothed to obtain 72 recent-period observations that represented measured deformation for periods ranging from 25 days to almost 5 years (fig. 11). The selection of the timing and duration of observations were guided by trends of measured deformation (fig. 11*A*). Seasonal trends of total compaction, residual compaction, and expansion and periods of transition from compaction to expansion, or vice-versa, were delineated by 24 short-term and 22 seasonal observations that ranged from 25 to 256.25 days (fig. 11*B*). Fourteen long-term observations that ranged from 281.25 to 743.75 days and 12 cumulative observations that ranged from 112.375 to 2,112.375 days corresponded to longer vertical-deformation trends. Figure 11 shows the timing and span of recent-period observations and their relation, in time, to daily vertical deformation. Recent observations ranged from 0.0056 ft of expansion to 0.0894 ft of compaction and averaged 0.0147 ft of compaction.

Observation Weights

Observation weights quantify each observation's relative influence on the regression. Accurate observations and observations that are especially important to the regression typically are assigned relatively high weights. Weights for Lorenzi observations primarily were based on the importance of observations to the regression, although observation accuracy, which generally was unknown, was considered.

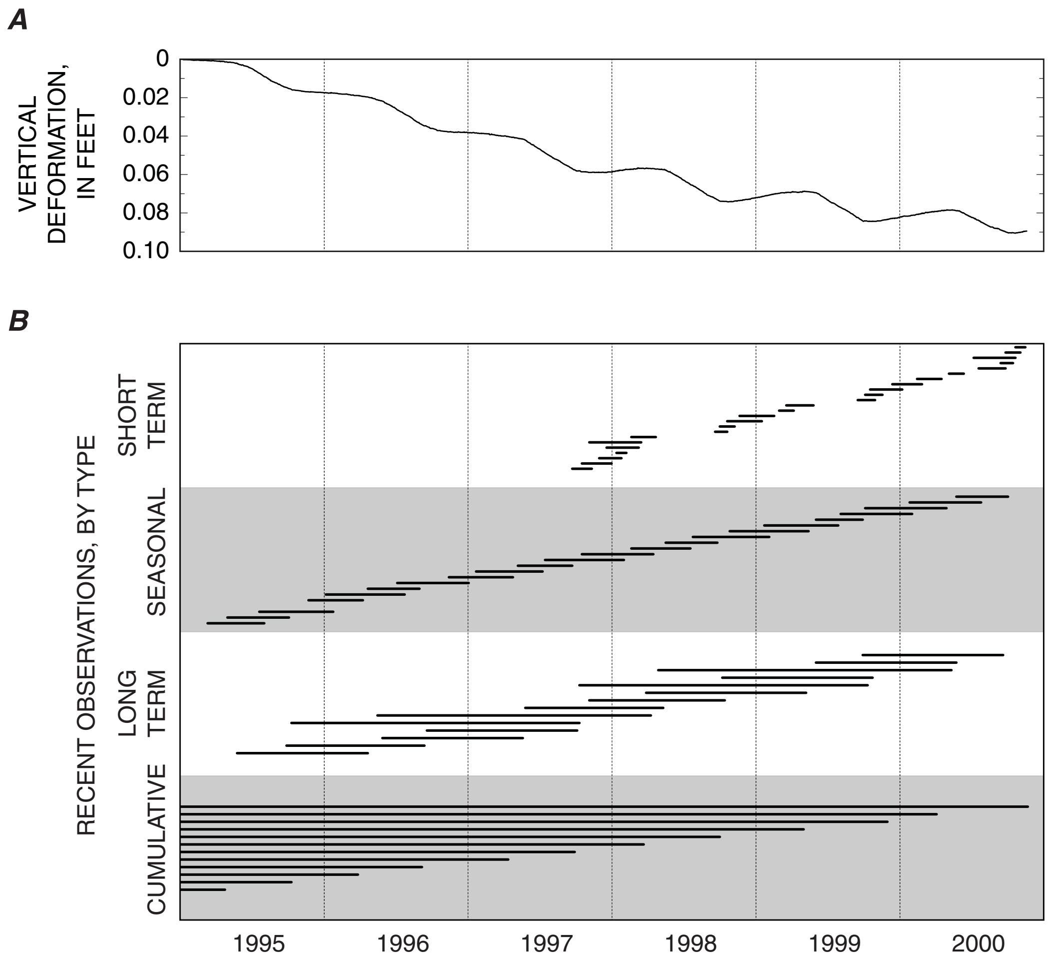


Figure 11. Graphs showing (*A*) daily deformation measured at USGS-EXT1 and (*B*) time spans for recent-period observations, by observation type, for the Lorenzi model, Las Vegas, Nevada.

In UCODE, the weight is calculated as the inverse of the variance of measurement error of an observation. For the Lorenzi model, a standard deviation or coefficient of variation for observation errors were input and the variance and weight were calculated by UCODE from these quantities.

Historic observation errors were caused by survey-measurement errors, contouring errors, and estimation errors. The observation errors were too difficult to quantify accurately; instead, errors were assumed to be related to the magnitudes of the observations. For years with repeat benchmark surveys, the actual amount of compaction was assumed to be within ±50 percent of the estimated observation values and, for years without repeat surveys, the actual amount of compaction was assumed to be within ±100 percent of the estimated observation values. These assumptions were used to calculate a coefficient of variation of 0.25 for observations in years with repeat surveys and 0.50 for observations in years without repeat surveys, except 1901. For the 1901 observation, a standard deviation of 0.005 ft was assigned because no compaction occurred by 1901 and a zero value cannot be assigned a coefficient of variation. Table 2 shows historic observations, error statistics, and weights.

Recent observation errors included extensometer-measurement errors and inaccuracies resulting from smoothing extensometer data. The extensometer-measurement errors resulted from the resolution of the measuring device and frictional and thermal effects (Pavelko, 2000). Errors associated with the resolution of the measuring device likely were insignificant relative to the frictional and thermal effects. Frictional "stick-slip" effects were caused by instantaneous releases of frictional energy created by the extensometer pipe rubbing against the borehole casing (Riley, 1986) and resulted in false step-like shifts in the recorded deformation data (Pavelko, 2000). Stick-slip effects greater than 0.0001 ft were removed from the record by shifting data after the event to align with data

Table 2. Historic observations and weight-related statistics used with the Lorenzi model, Las Vegas, Nevada

[The 1901 weight was based on a standard deviation and for all other historic observations, UCODE calculated weights based on coefficients of variation. Observations with a coefficient of variation of 0.25 correspond to years with repeat benchmark surveys. Abbreviations: ft, feet; ft^2, square feet; --, not applicable]

Year of observation	Observation value (ft)	Coefficient of variation	Standard deviation (ft)	Variance (ft^2)	Weight ($1/ft^2$)
1901	0.00	--	5.0×10^{-3}	2.5×10^{-5}	4.0×10^{4}
1935	0.01	0.50	5.0×10^{-3}	2.5×10^{-5}	4.0×10^{4}
1941	0.03	0.25	7.5×10^{-3}	5.6×10^{-5}	1.8×10^{4}
1944	0.08	0.50	4.0×10^{-2}	1.6×10^{-3}	6.3×10^{2}
1947	0.13	0.50	6.5×10^{-2}	4.2×10^{-3}	2.4×10^{2}
1950	0.18	0.25	4.5×10^{-2}	2.0×10^{-3}	4.9×10^{2}
1953	0.22	0.50	1.1×10^{-1}	1.2×10^{-2}	8.3×10^{1}
1957	0.28	0.50	1.4×10^{-1}	2.0×10^{-2}	5.1×10^{1}
1960	0.32	0.50	1.6×10^{-1}	2.6×10^{-2}	3.9×10^{1}
1963	0.36	0.25	9.0×10^{-2}	8.1×10^{-3}	1.2×10^{2}
1966	0.49	0.50	2.5×10^{-1}	6.0×10^{-2}	1.7×10^{1}
1969	0.63	0.50	3.2×10^{-1}	9.9×10^{-2}	1.0×10^{1}
1972	0.76	0.25	1.9×10^{-1}	3.6×10^{-2}	2.8×10^{1}
1975	0.89	0.50	4.5×10^{-1}	2.0×10^{-1}	5.0×10^{0}
1977	0.98	0.50	4.9×10^{-1}	2.4×10^{-1}	4.2×10^{1}
1980	1.10	0.25	2.8×10^{-1}	7.6×10^{-2}	1.3×10^{0}
1983	1.23	0.50	6.2×10^{-1}	3.8×10^{-1}	2.6×10^{0}
1986	1.36	0.25	3.4×10^{-1}	1.2×10^{-1}	8.7×10^{0}
1989	1.45	0.50	7.3×10^{-1}	5.3×10^{-1}	1.9×10^{0}
1992	1.55	0.50	7.8×10^{-1}	6.0×10^{-1}	1.7×10^{0}
1994	1.60	0.50	8.0×10^{-1}	6.4×10^{-1}	1.6×10^{0}

from before the event. Frictional “dead-band” effects (Riley, 1986), which can be difficult to detect in an extensometer record, also were likely present in the extensometer data, but no effort was made to correct for them.

Daily temperature fluctuations of as much as 55°F in the extensometer shed caused components of the extensometer to thermally expand and contract, which resulted in recorded daily fluctuations (fig. 9) that likely reflected diurnal temperature trends rather than deformation trends (Pavelko, 2000). To minimize the effects of daily temperature fluctuations on the extensometer record, while maintaining longer-term trends, the extensometer data were smoothed.

The combined errors associated with the resultant observation data set were too difficult to quantify accurately. The errors were assumed the same for all recent observations because each consisted of two measurements made by the same device. Thus, a standard deviation was estimated to determine weights rather than a coefficient of variation, which would have assigned weights based upon the magnitude of observation values. To estimate the standard deviation, several sets of weighting schemes were tested with UCODE runs. When weights were skewed to emphasize the historic period, historic observations were simulated well but recent observations were matched poorly. Similarly, when weights were skewed to emphasize the recent period, the recent period was simulated well but the historic period was simulated poorly. Trial-and-error weight adjustments indicated that a balanced simulation of the two periods would result when recent observation errors were assigned a standard deviation of 0.005 ft. Implications and limitations to assigning qualitatively derived weights are discussed in the Sensitivity section.

Sensitivity

The sensitivity of the model to parameter values, observation values, observation weights, and the conceptual model was analyzed with sensitivity statistics and by testing alternative conceptual and numerical models. Sensitivity statistics reveal information about how sensitive a model is to changes in parameter values and how important observations are to estimating parameters. Parameter sensitivities calculated by UCODE for the calibrated model were analyzed to determine if the numerical model and observation data provided enough information to adequately estimate the parameters (Hill, 1998). Sensitivity to model thicknesses, initial preconsolidation heads, and observation weights also were tested.

The composite scaled sensitivity (CSS) of an estimated parameter represents the sensitivity of a model to a change in a parameter value, summarizes the importance of all observation data to estimating the parameter, and is defined as:

$$CSS = \left[\frac{\sum_{i=1}^{n} w_i \left(\frac{\partial y'_i}{\partial b} b \right)^2}{n} \right]^{\frac{1}{2}}, \qquad (9)$$

where b is the parameter value. Relatively large CSS values indicate that the simulated equivalents of the observation data are sensitive to those parameters and therefore those parameters are more likely to be adequately estimated. If estimation by regression is attempted for parameters with CSS values less than 0.01 times the largest CSS value, the regression may have difficulties converging and the estimated parameter values may not be accurate or unique. The CSS values calculated for the estimated parameters (fig. 12) indicated that the model and observation data provided sufficient information to estimate the parameters by regression because the largest CSS value was less than 100 times the smallest CSS value (Hill, 1998).

Dimensionless scaled sensitivity (DSS) values (Hill, 1992) were calculated for each observation. DSS values are used to determine the importance of individual observations to estimating each parameter value and the importance of individual parameters to calculating simulated observation values (Hill, 1998). Generally, observations that represented more deformation had relatively large absolute values of dimensionless scaled sensitivities, which indicated that they were more important to the regression than observations that represented less deformation. DSS values also indicated that all observations generally were most sensitive to S'_{skv}, shorter-term observations were relatively more sensitive to S_{ske}, and longer-term observations were relatively more sensitive to S'_{skv}. The relatively large CSS and DSS values for S'_{skv} indicated that observation data as a whole are most sensitive to that parameter.

Simulated deformation was sensitive to the thickness of the simulated aquifer system. Because UCODE does not evaluate aquifer thickness, a sensitivity

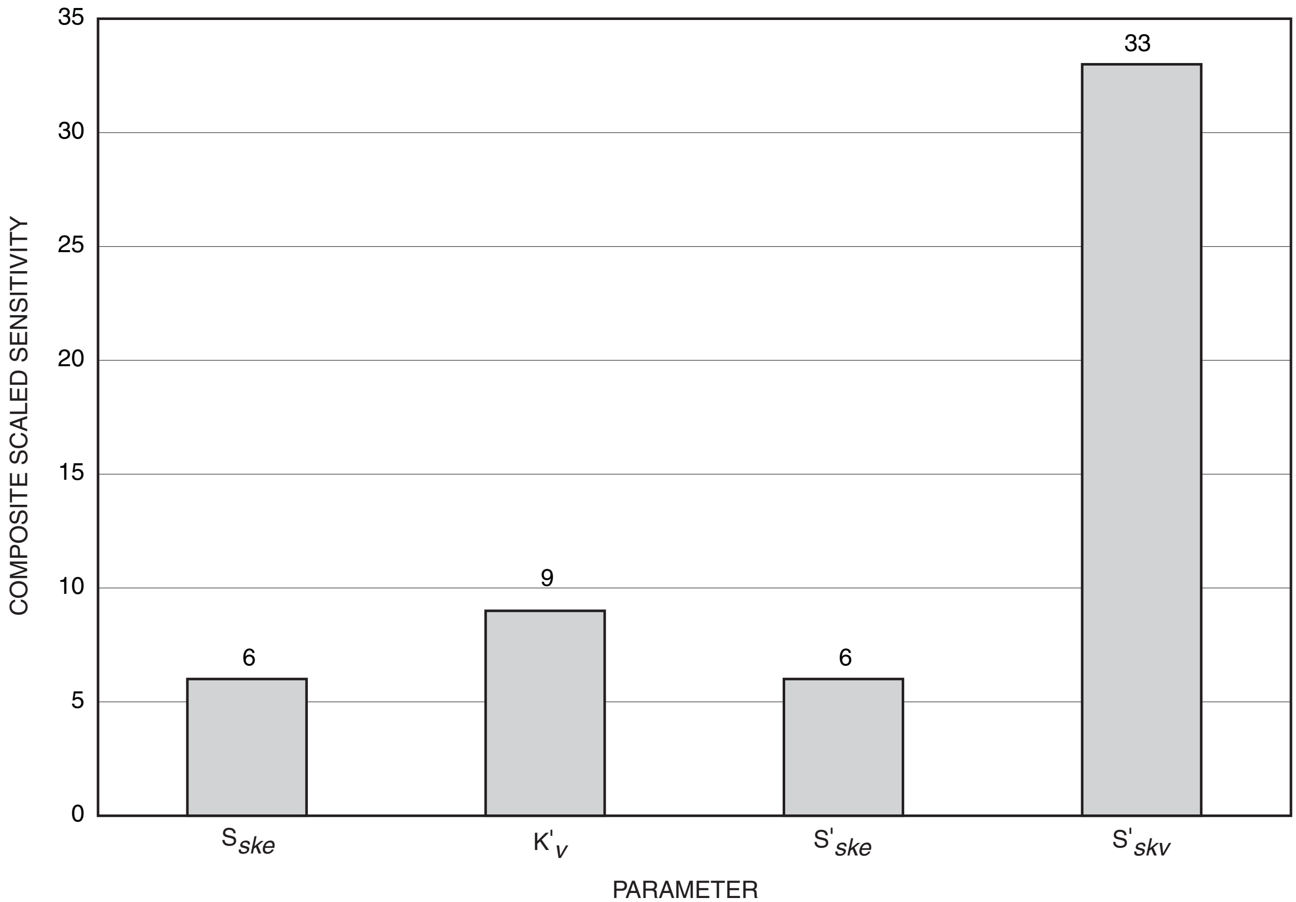


Figure 12. Composite scaled sensitivities for the estimated parameters of the Lorenzi model, Las Vegas, Nevada.

analysis was done to determine the magnitude of change, if any, an increased aquifer thickness would have on estimated hydraulic-property values, simulated deformation, and simulated aquitard heads. Although data only support a model no deeper than 800 ft below land surface, a thicker, simplified conceptual model was constructed by repeating below the original model the 735-ft sequence of sediments measured with geophysical methods (fig. 5). The 1,470-ft thick model approximates Plume's (1989) estimate of about 1,600 ft of sediments at the Lorenzi site. Regression-derived estimates of hydraulic properties from the thicker model ranged from about two times higher (S'_{skv}) to three orders-of-magnitude lower (S_{ske}) than calibrated model estimates. Additionally, the deformation and aquitard-head profiles simulated with the thicker model did not adequately match estimated or measured data. Therefore, the sensitivity analysis indicates that the thickness of the calibrated conceptual model more appropriately simulated deformation than the thicker model, but does not confirm that there are no compactible sediments below 800 ft.

Simulated deformation was sensitive to initial preconsolidation heads, which were not considered in sensitivity statistics. To examine the sensitivity to initial preconsolidation heads, the 1.65 ft of total simulated deformation from the final model was compared to simulated deformation from alternative models. When initial preconsolidation heads were increased by 10 ft, total deformation was 1.72 ft and when initial preconsolidation heads were deceased by 10 ft, total deformation was 1.58 ft. The significant figures of these simulated values are given only to show the variation produced when changing initial preconsolidation heads and do not imply a level of accuracy.

Model Fit

Model fit was evaluated by comparing simulated deformation to observation data, examining regression-error statistics, and analyzing weighted residuals. A good model fit indicates that, at the scale of the model and given the simplifying assumptions and limitations, the estimated parameter values are representative of the hydraulic-property values. The close match between simulated deformation and observation data indicates a good model fit that can be seen in a plot comparing simulated, observed, and measured deformation (fig. 13) and a plot of simulated versus observed deformation values (fig. 14). These plots are unaffected by the weights associated with observations and therefore provide an analysis independent of weights and any uncertainties associated with the weights.

The standard error of regression and fitted error statistics are quantitative measures of model fit (Hill, 1998). The standard error of regression (s) is a measure of overall model fit to the weighted observation data, and is computed as:

$$s = \left(\frac{S}{n-p}\right)^{\frac{1}{2}}, \tag{10}$$

where S is the sum of weighted squared residuals for all observations and p is the number of estimated parameters. For a model fit that is consistent with

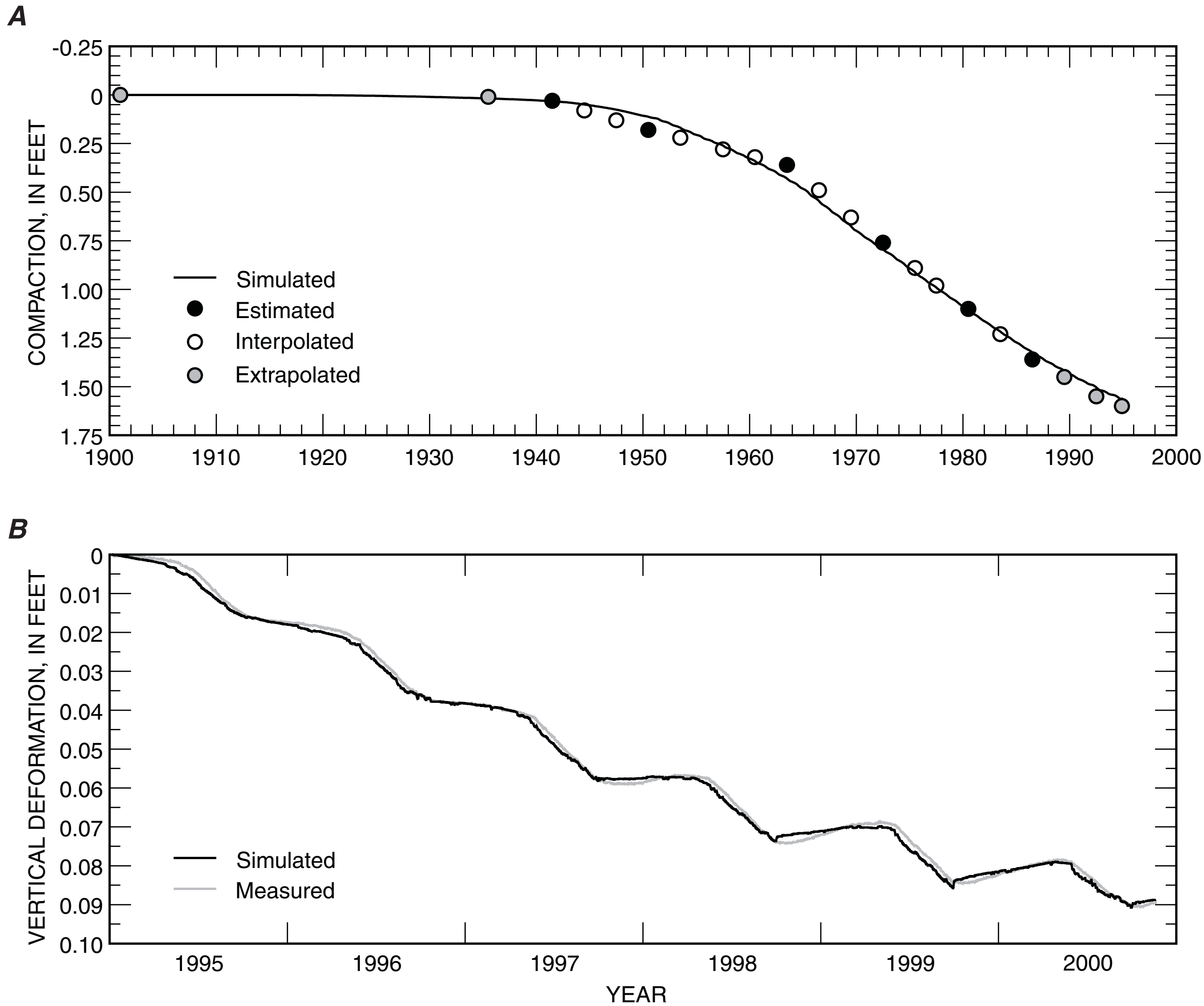


Figure 13. Graphs showing (*A*) historic simulated and estimated and (*B*) recent simulated and measured deformation data for the Lorenzi model, Las Vegas, Nevada

observation-data accuracy, as indicated by the weighting, *s* is 1.0. The standard error of the Lorenzi regression was 0.36, which indicated that simulated deformation fit observed data better than the weighting implied, but did not indicate a lack of model error. Trial-and-error weighting adjustments for the Lorenzi model indicated that the best combination of model fit and regression statistics was achieved with the weights used in the calibrated model. The standard error of the Lorenzi model is only as accurate as the estimated weights and therefore the standard error is more representative of model fit to the conceptual model and observation data rather than a measure of model fit to the real system.

Fitted error statistics represent the overall fit achieved for simulated values (Hill, 1998). Fitted error statistics are more intuitive measures of error than the standard error because they have the same units as the observed values. The statistics are calculated by multiplying *s* by the statistic used to calculate weights. For

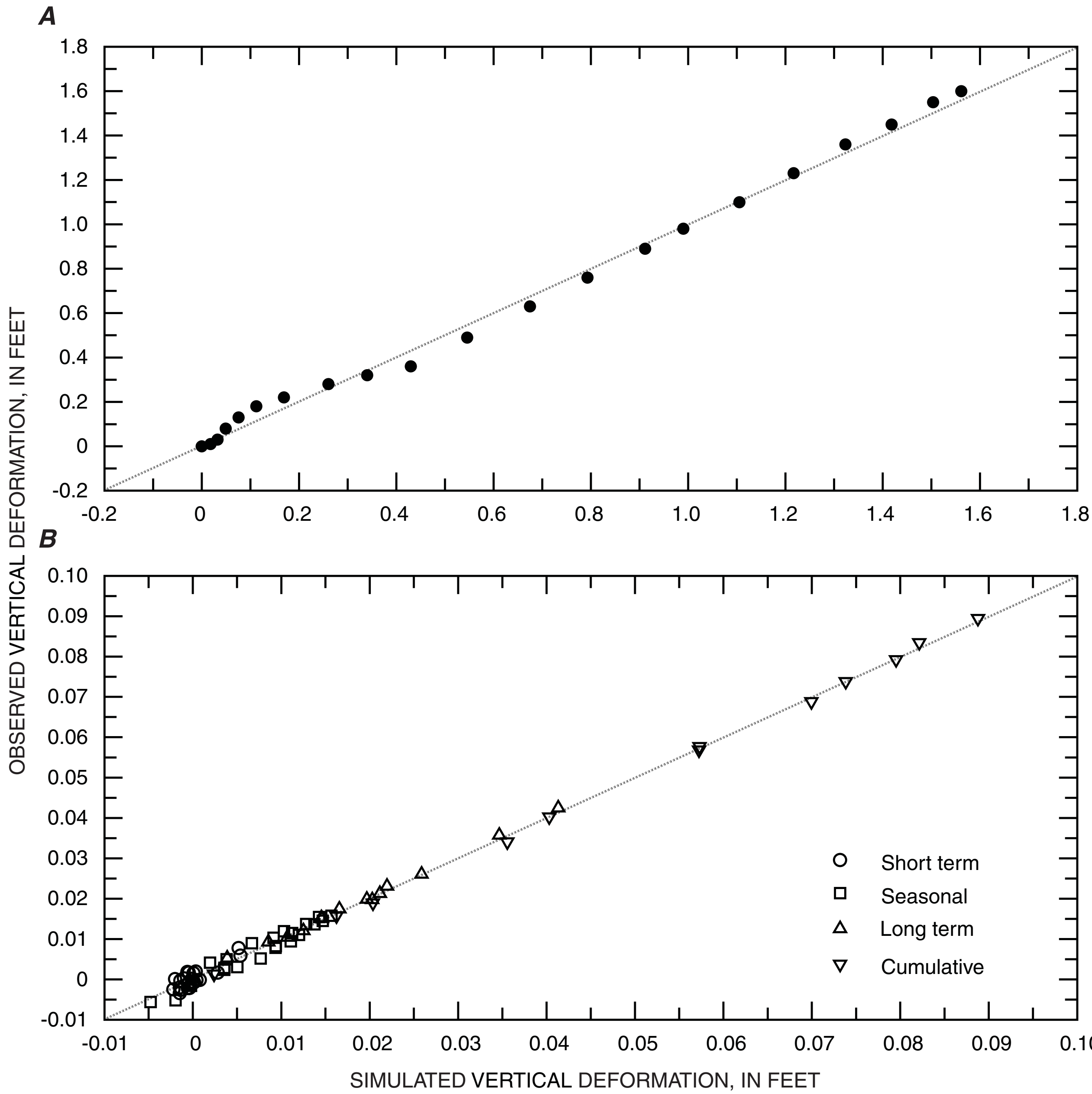


Figure 14. Simulated deformation versus observed deformation for (*A*) the historic period and (*B*) the recent period of the Lorenzi model, Las Vegas, Nevada.

example, the fitted standard deviation of recent observations (0.002 ft) was the standard error (0.36) multiplied by the standard deviation of recent observations (0.005 ft). The fitted standard deviation indicated that, overall, simulated deformation values for the recent period matched the 72 observed values within 0.002 ft. The fitted coefficient of variation was 0.18 ft for the 14 historic-period observations for years without surveys and 0.09 ft for the 6 historic-period observations for years with surveys. Fitted error statistics generally are meaningful only for a large number of observations (Hill, 1998) but were presented for the historic period as general indicators of the errors associated with that period.

A weighted residual is the difference of an observed value and simulated value, multiplied by the square root of the observation weight. Weighted residuals, which were evaluated individually and as groups, are indicators of observation errors, model fit, and the validity of a regression.

Weighted residuals with significantly larger absolute values than other weighted residuals indicate possible problems with observation data or model fit, or both. Five historic and three recent weighted residuals have absolute values greater than 0.5 (fig. 15), indicating that, generally, few problems exist associated with observation data or model fit. Historic period outliers likely resulted from inaccurate observation values or

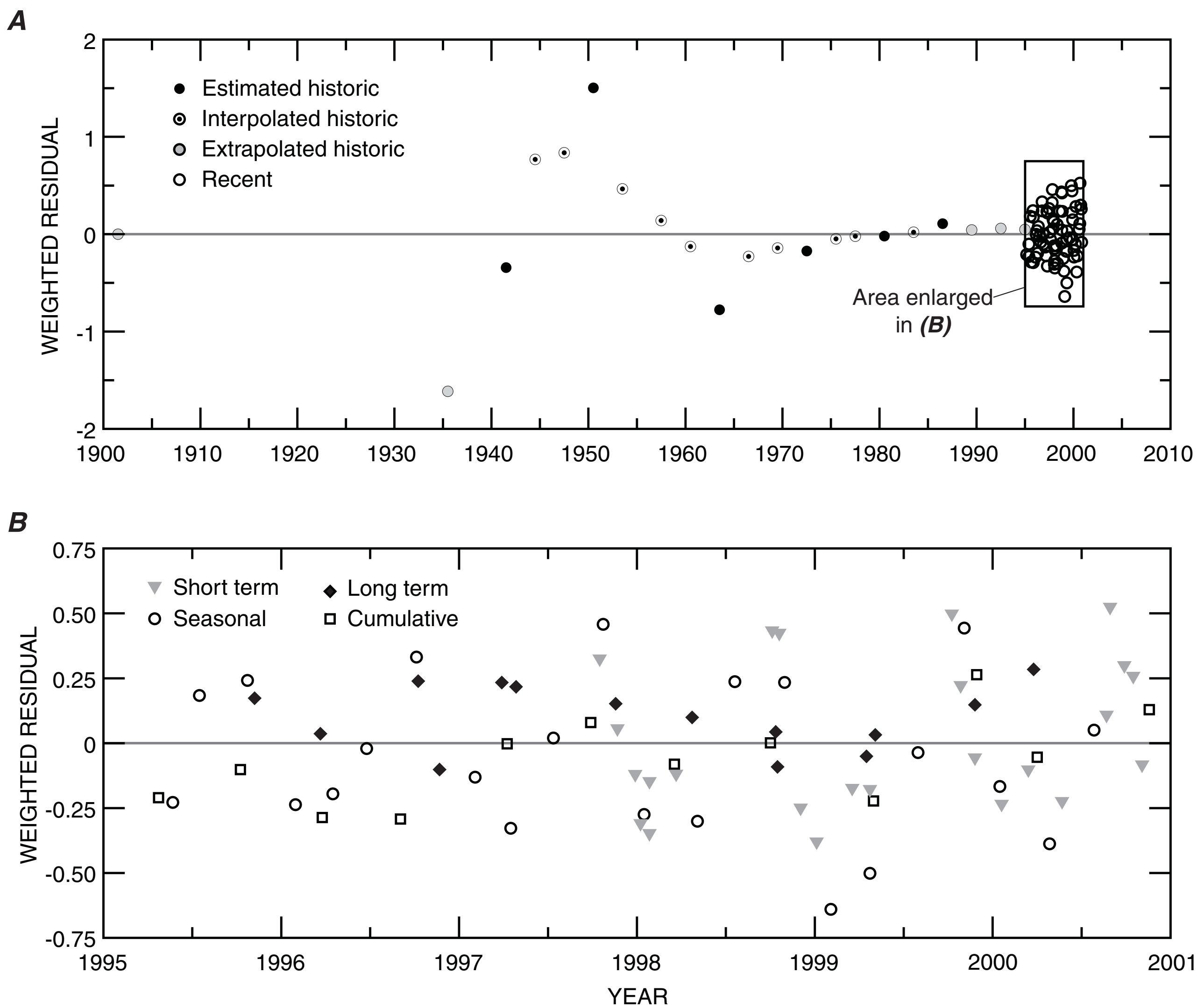


Figure 15. Weighted residuals versus time for the (*A*) entire model and (*B*) recent period of the Lorenzi model, Las Vegas, Nevada.

weights, whereas recent period outliers, which were associated with transitional periods and periods of expansion, likely resulted from errors in the optimal estimated hydraulic-parameter values, but mechanical inefficiencies associated with the extensometer may have had an effect. The generally good model fit (figs. 13 and 14) indicates that the weighted residual outliers do not indicate significant model errors.

ESTIMATED PARAMETER VALUES

The estimated parameter values from the calibrated Lorenzi model were obtained after evaluating the conceptual model, testing different sets of parameters to be estimated, and evaluating regression statistics for different observation and weighting scenarios. Optimal hydraulic-parameter estimates for the Lorenzi model are 3 x 10^{-6} ft/d for K'_v, 4 x 10^{-5} ft^{-1} for S'_{skv}, 5 x 10^{-6} ft^{-1} for S'_{ske}, and 3 x 10^{-7} ft^{-1} for S_{ske} (table 3).

The true property values of a physical system cannot be accurately quantified and therefore the accuracy of the estimated values cannot be quantified. The accuracy of the estimated values, then, were assessed on how reasonable the values were based on what was known about this and other similar systems; correlation coefficients; and simulated conditions, including model fit to observed data (figs. 13 and 14) and adherence to the conceptual model.

Unreasonable parameter estimates are indicators of model error (Hill, 1998) because it is reasonable to expect that parameter values associated with the minimized objective function are realistic values, providing that the physical system is adequately represented by the model and the observation data provide sufficient information about the estimated parameters. For the calibrated model, the estimated values were within their reasonable ranges (table 3; see the Hydraulic Properties section).

Parameter correlation coefficients are a measure of the interdependence of two parameters and were analyzed to determine if parameter values could be uniquely estimated with the information provided by the model and observation data (Hill, 1998). Correlation coefficients can range from -1.0 to 1.0 and absolute values greater than 0.95 are indicative of potential problems for unique parameter-value estimation (Hill, 1998). For the Lorenzi model, no parameters were correlated above 0.60, indicating that the estimated values were unique and relatively unaffected by model or observation errors.

Simulated Conditions

A calibrated model should produce a good model fit and agree with the conceptual model. Based on comparisons of observed and simulated data (figs. 13 and 14), examination of regression error statistics, and analyses of weighted residuals, as discussed in the Model Fit section, the model fit to aquifer-system deformation data was considered sufficient and therefore indicates that the estimated parameter values were reasonable.

Table 3. Reasonable ranges and optimal estimates for the hydraulic parameters estimated with the Lorenzi model, Las Vegas, Nevada

[Abbreviations: K'_v, aquitard vertical hydraulic conductivity; S'_{skv}, aquitard inelastic skeletal specific storage; S'_{ske}, aquitard elastic skeletal specific storage; S_{ske}, aquifer elastic skeletal specific storage; ft/d, feet per day; 1/ft, per feet]

	K'_v	S'_{skv}	S'_{ske}	S_{ske}
	(ft/d)	(1/ft)		
Upper reasonable value	7 x 10^{-3}	1 x 10^{-3}	2 x 10^{-5}	2 x 10^{-6}
Optimal estimate	3 x 10^{-6}	4 x 10^{-5}	5 x 10^{-6}	3 x 10^{-7}
Lower reasonable value	2 x 10^{-6}	7 x 10^{-6}	1 x 10^{-6}	3 x 10^{-8}

Simulated aquitard heads, estimated aquitard time constants, and simulated vertical deformation were examined to determine if simulated data were in agreement with the conceptual model. If the physical system was adequately represented and observation data were sufficient, simulated delayed aquitard drainage and associated residual compaction would be expected. Figure 16 shows that aquitard heads declined much more slowly than aquifer heads and that during the recent period, when aquifer heads generally were rising, aquitard heads continued to decline. Figure 17 shows that delayed aquitard drainage was associated with simulated residual compaction. Figure 17*B* shows that during the recent period, residual compaction occurred in aquitards when aquifer heads were recovering. An indicator of the rate of residual compaction is the time constant, τ, which describes how long a doubly draining aquitard will take to achieve about 93 percent of the total possible compaction for a given head decline (eq. 1; Riley, 1969). Strictly speaking, the aquitards at the Lorenzi site are not doubly draining; the shallow aquitard only drains downward and the simulated heads in the three aquifers are not identical. At the end of the simulated period, the approximate simulated heads were 217 ft below land surface for the shallow aquifer, 251 ft below land surface for the middle aquifer, and 262 ft below land surface for the deep aquifer. A modified equation (Epstein, 1987), described in the Mechanics of Vertical Aquifer-System Deformation section of this report, was used to calculate τ for the shallow aquitard, and, despite the discrepancies in aquifer heads, an approximate τ was calculated to determine if residual compaction based on estimated properties conformed to the conceptual model. The shallow, middle, and deep aquitards had time constants that were about 1,310; 110; and 100 years, respectively. The values conform to the conceptual model because they indicate that the middle and deep aquitards, which

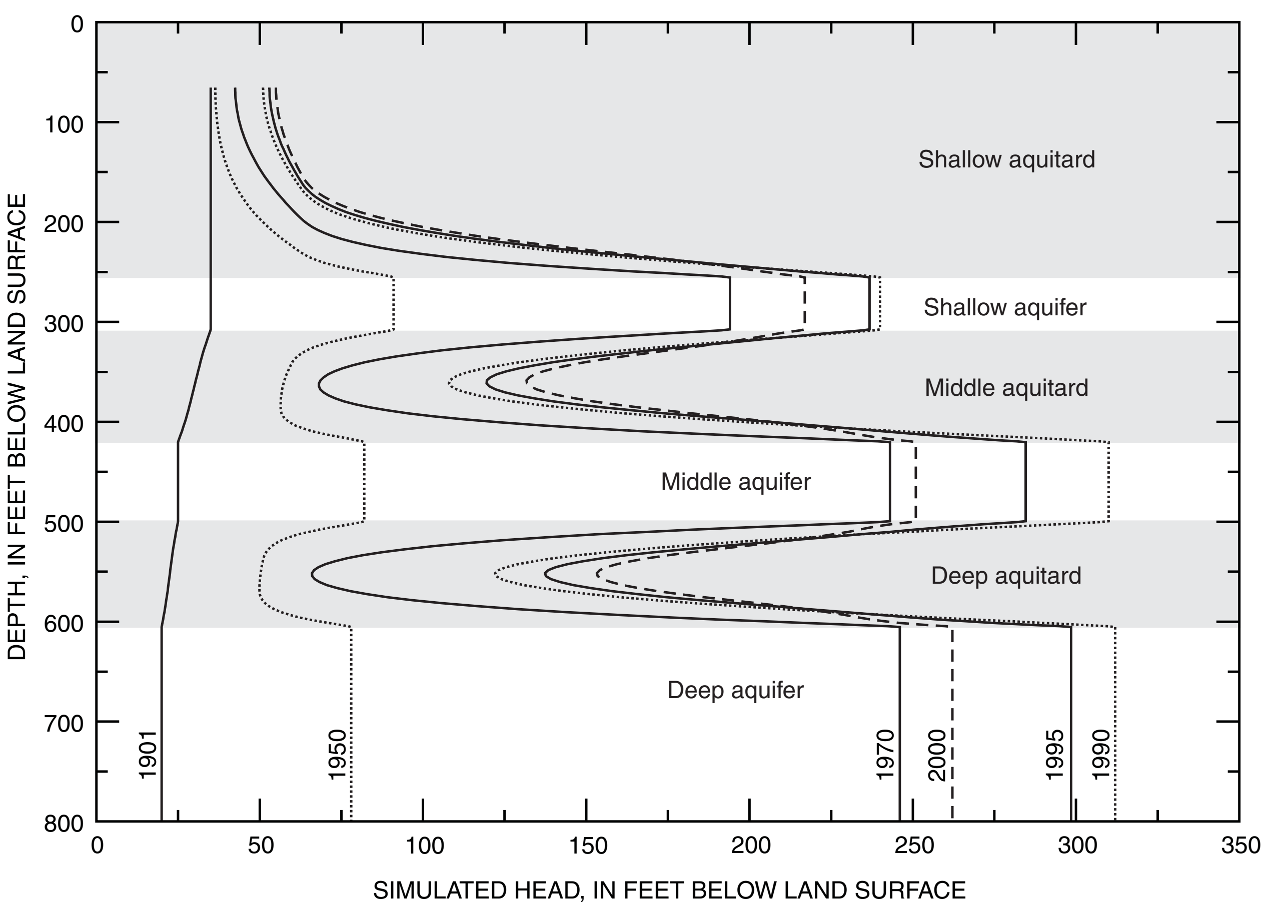


Figure 16. Simulated heads for selected years of the Lorenzi model, Las Vegas, Nevada.

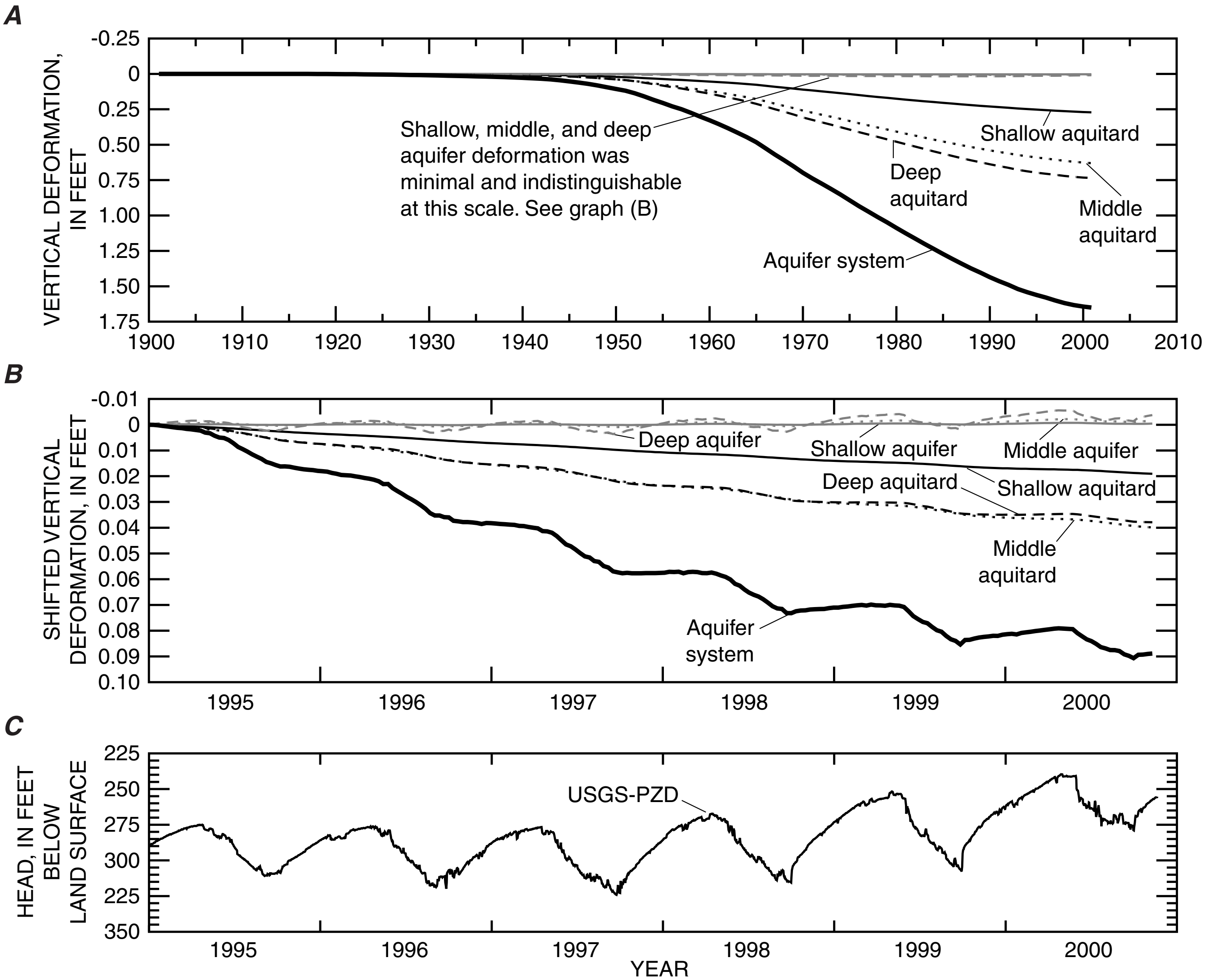


Figure 17. Simulated deformation, by aquifer system and aquifer-system unit, for (*A*) the entire model and (*B*) the recent period, and (*C*) USGS-PZD specified heads, for the recent period of the Lorenzi model, Las Vegas, Nevada.

are approximately doubly draining and relatively thin, will achieve about 93 percent of their ultimate compaction much faster than the shallow aquitard, which is singly draining and about 55 percent thicker than the middle and deep aquitards.

MODEL AND REGRESSION LIMITATIONS

The Lorenzi numerical model was limited by the accuracy of the conceptual model, simplifications and limitations inherent in the mathematical codes that represented the physical systems and processes, and the availability and accuracy of data. A primary cause of Lorenzi model limitations was insufficient or inaccurate data. A lack of data necessitated simplifications, and therefore limitations, in the conceptual and numerical models; observation-data errors that could not be quantified resulted in subjective observation weights; and a lack of aquitard-head data resulted in an objective function that allowed for poorly simulated heads. These limitations affected the usefulness of regression statistics and the estimation and accuracy of the estimated hydraulic-property values. Limitations also arose from assumptions and simplifications embedded in the computer codes that made up the model.

The lack of sufficient data to account for all of the spatial variations in physical and hydraulic properties required that the Lorenzi conceptual and numerical models were 1-D simplifications of the surrounding ground-water flow system, ground-water flow processes, and vertical-deformation processes. Furthermore, any data used in the model but not as observation data, such as initial heads, initial preconsolidation heads, and specified aquifer heads, likely had inaccuracies that affected simulations. The simplifications and data errors likely affected the magnitude and timing of simulated deformation and resulted in estimated property values that were averages for the unit types.

Compaction data for the Lorenzi site could not support a model that estimated separate hydraulic-property values for each aquifer-system unit or more than one value per unit. Instead, each unit type was assumed to be homogeneous and have an identical set of hydraulic-property values. This assumption resulted in hydraulic-property estimates that are averages for the composite thickness of each unit type and not necessarily representative of a particular depth interval.

The limiting effects of data on the objective function are related to the accuracy of the observation-data weights and the types of data included within the objective function. During the iterative calibration process, several weighting scenarios were tested, but because weights were included in many of the diagnostic statistics, including the objective function, statistical comparisons of model results were misleading if the runs did not have the same weights. Therefore, (1) weighting schemes were chosen subjectively, based on visual matches to observation data and the reasonability of simulated aquitard heads and estimated parameter values and (2) diagnostic statistics were helpful during calibration to identify runs that were bad, but the statistics could not be used as comparative tools for runs with different weighting schemes.

The objective function, and therefore the estimated parameter values, also was affected by a lack of variety of data. Ideally, the objective function, and therefore observation data, should include as many types of data and as much data as reasonably possible. The Lorenzi model simulated vertical deformation and aquitard heads, but there were no aquitard-observation data. The lack of aquitard observations resulted in several intermediate runs that fit the deformation-observation data well, but did not fit the conceptual model. For example, figure 18 is a plot of simulated heads for the calibrated model and an intermediate run that was identical except that the recent period weights were larger. The two runs had simulated deformation curves that were very similar, but the intermediate run had simulated aquitard heads that conceptually were not correct because there was almost no delayed drainage within aquitard units. The objective function as a diagnostic tool was misleading because although the two runs had comparable objective function values (good fits to deformation) the intermediate run was a much worse run because of the poorly simulated aquitard heads. Inclusion of aquitard-head data as an observation would have improved the value of the objective function.

Model and regression limitations also resulted from documented limitations associated with the various computer codes used in the model (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; Leake and Lilly, 1997; Leake and Prudic, 1991; Poeter and Hill, 1998). In particular, the IBS1 package does not calculate deformation for specified-head cells, which likely resulted in a slight underestimation of aquifer deformation or a slight overestimation of storage values, or both. All specified-head cells in the Lorenzi model were 1-ft thick, which equated to an aggregate thickness of 5 ft, or about 0.7 percent of the total model thickness. Another limitation arose from the assumption embedded within the IBS1 package that elastic aquifer-system deformation is proportional to effective stress changes and that inelastic compaction is proportional to effective stress increases, even though inelastic aquitard compaction is more likely proportional to increases in the logarithm of effective stress (Jorgensen, 1980; Leake and Prudic, 1991). Leake and Prudic indicate that errors resulting from this assumption are minimal.

The deformation formulation used in the IBS1 package (Leake and Prudic, 1991) is based on the assumption that within a model cell a change in head will result in an instantaneous change in ground-water storage. Thus, deformation in individual model cells occurs instantaneously with a change in head rather than at a rate controlled by hydraulic properties. This shortcoming for simulating delayed drainage and residual compaction was minimized by using a finely discretized model grid for aquitards.

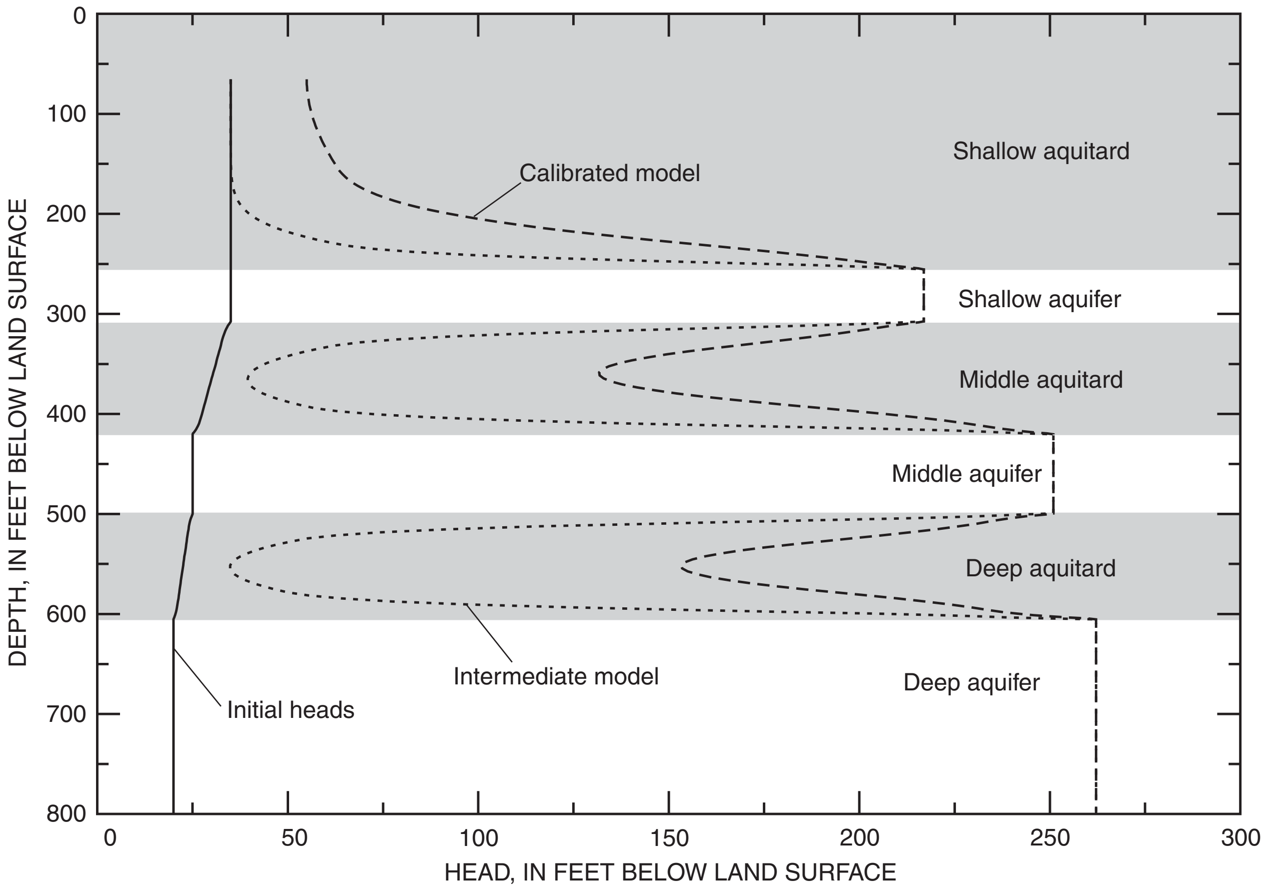


Figure 18. Initial heads and simulated head profiles for the calibrated model and an intermediate model, for 2000, the Lorenzi model, Las Vegas, Nevada.

SUMMARY AND CONCLUSIONS

Las Vegas is in Las Vegas Valley, in southern Nevada, and is the Nation's fastest growing metropolitan area. Decades of ground-water withdrawals have resulted in aquifer-system compaction, over 5 ft of land subsidence, and earth fissuring. Since 1988, artificial ground-water recharge programs have slowed the rate of subsidence and caused seasonal aquifer-system expansion and land uplift. The aquifer system at the Lorenzi site, which is in Las Vegas and monitors ground-water levels and vertical aquifer-system deformation, was numerically modeled to estimate hydraulic properties that affect vertical aquifer-system deformation.

The conceptual model used to construct the numerical model was based on geophysical and lithologic logs collected at the site and established theories of aquifer-system mechanics. The numerical model consisted of three thick aquifers and three thick aquitards. Fine spatial discretization of the model allowed for the simulation of residual compaction; fine temporal discretization allowed for better analyses of short-term deformation trends and nonlinear-head distributions. Ground-water flow, and therefore aquifer-system deformation, was controlled entirely by transient heads that were specified for selected aquifer cells.

The model simulated ground-water flow and vertical aquifer-system deformation from January 1, 1901, to November 19, 2000. The initial conditions and specified heads for the historic period, 1901–94, were estimated from previously published reports. For the recent period, 1995–2000, specified heads were daily average heads collected at the Lorenzi site.

Nonlinear-regression techniques were applied to the model for calibration and estimation of aquitard vertical hydraulic conductivity, aquitard inelastic skeletal specific storage, and aquitard and aquifer elastic skeletal specific storage. The observation data used for the regression consisted of 21 estimates of compaction for the historic period and 72 deformation measurements from smoothed extensometer data for the recent period.

The optimal estimates for the hydraulic properties were: 3 x 10^{-6} ft/d for aquitard vertical hydraulic conductivity, 4 x 10^{-5} ft^{-1} for aquitard inelastic skeletal specific storage, 5 x 10^{-6} ft^{-1} for aquitard elastic skeletal specific storage, and 3 x 10^{-7} ft^{-1} for aquifer elastic skeletal specific storage. The regression, and therefore estimated parameter values, was negatively affected by a lack of aquitard-head data. Acquiring and incorporating aquitard data into the model would have better constrained the regression and resulted in a more quantitative set of parameter estimates. Given the limitations of the numerical model to represent the physical system and inaccuracies related to observations, model fit, regression statistics, and simulated aquitard heads indicated that the numerical model and observation data provided sufficient information to estimate the target parameters, the regression was valid, and the estimated hydraulic-property values were reasonable.

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