Part I

Mining Ground Water

Santa Clara Valley, California

San Joaquin Valley, California

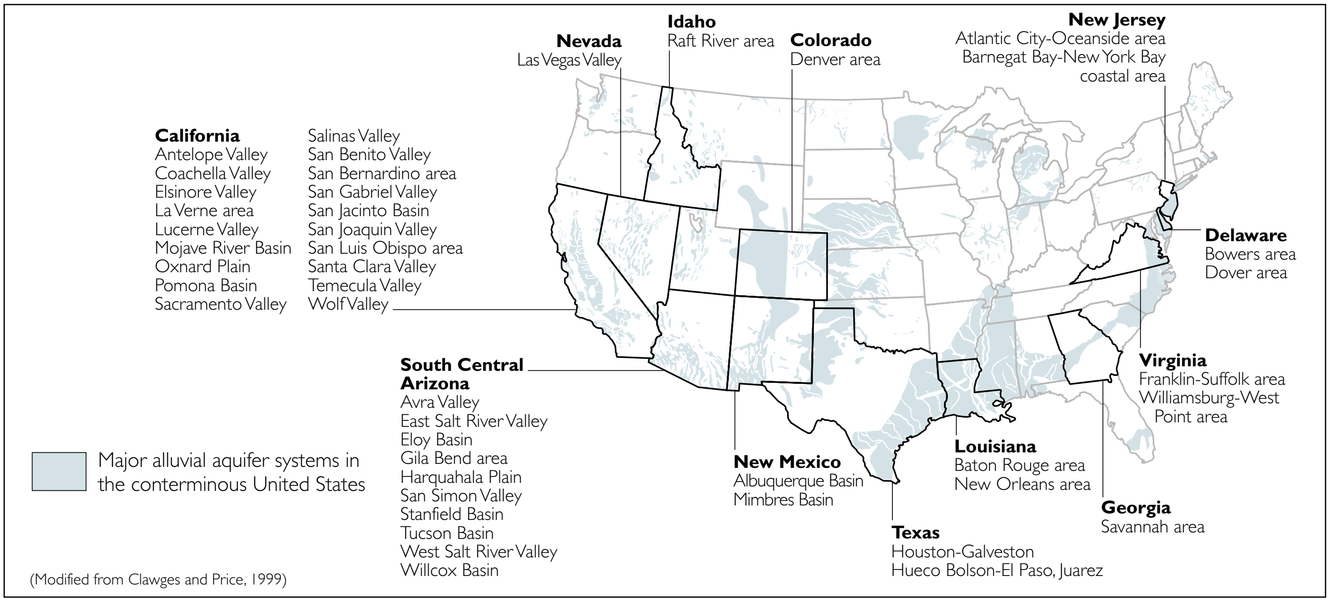
Houston-Galveston, Texas

Las Vegas, Nevada

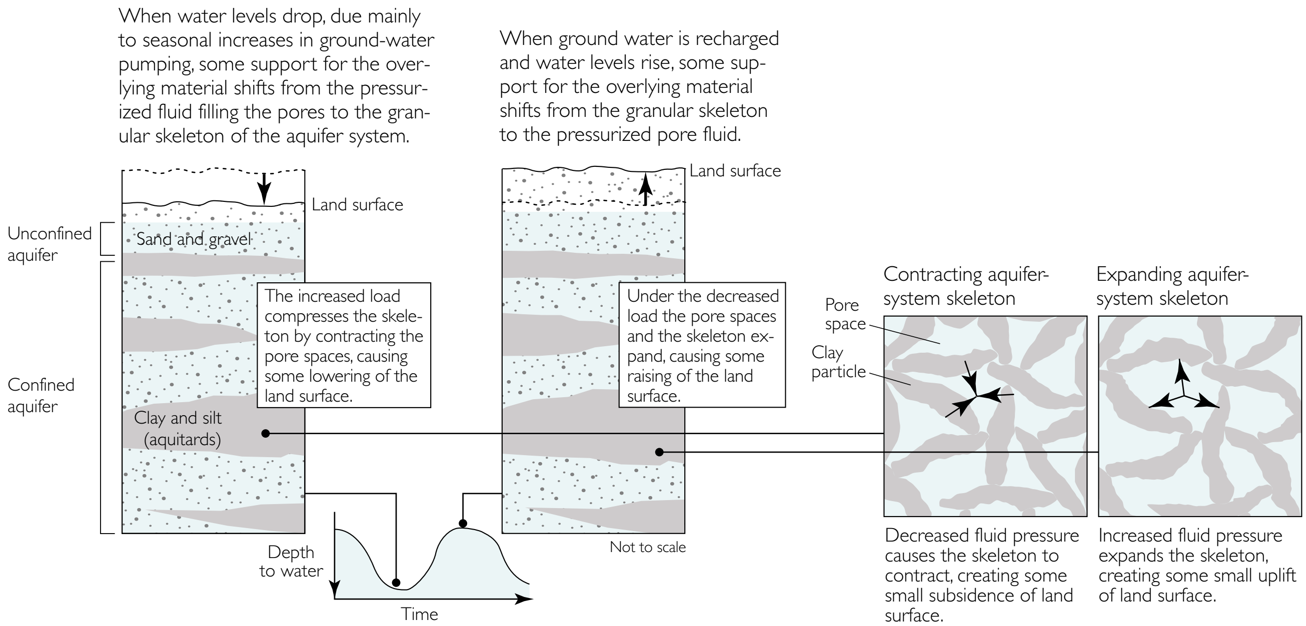
South-Central Arizona

Permanent subsidence can occur when water stored beneath the Earth's surface is removed by pumpage or drainage. The reduction of fluid pressure in the pores and cracks of aquifer systems, especially in unconsolidated rocks, is inevitably accompanied by some deformation of the aquifer system. Because the granular structure—the so-called "skeleton"—of the aquifer system is not rigid, but more or less compliant, a shift in the balance of support for the overlying material causes the skeleton to deform slightly. Both the aquifers and aquitards that constitute the aquifer system undergo deformation, but to different degrees. Almost all the permanent subsidence occurs due to the irreversible compression or consolidation of aquitards during the typically slow process of aquitard drainage (Tolman and Poland, 1940). This concept, known as the aquitard-drainage model, has formed the theoretical basis of many successful subsidence investigations.*

Areas where subsidence has been attributed to ground-water pumpage



* Studies of subsidence in the Santa Clara Valley (Tolman and Poland, 1940; Poland and Green, 1962; Green, 1964; Poland and Ireland, 1988) and San Joaquin Valley (Poland, 1960; Miller, 1961; Riley, 1969; Helm, 1975; Poland and others, 1975; Ireland and others, 1984) in California established the theoretical and field application of the laboratory derived principle of effective stress and theory of hydrodynamic consolidation to the drainage and compaction of aquitards. For reviews of the history and application of the aquitard drainage model see Holzer (1998) and Riley (1998).

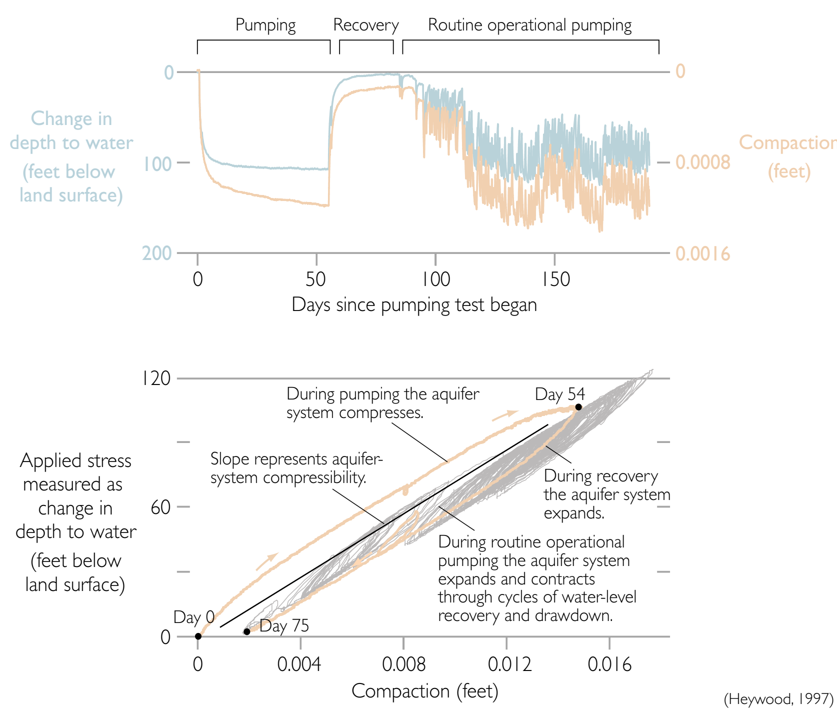


REVERSIBLE DEFORMATION OCCURS IN ALL AQUIFER SYSTEMS

The relation between changes in ground-water levels and compression of the aquifer system is based on the principle of effective stress first proposed by Karl Terzaghi (Terzaghi, 1925). By this principle, when the support provided by fluid pressure is reduced, such as when ground-water levels are lowered, support previously provided by the pore-fluid pressure is transferred to the skeleton of the aquifer system, which compresses to a degree. Conversely, when the pore-fluid pressure is increased, such as when ground water recharges the aqui-

Mostly recoverable (elastic) deformation was observed during and following a pumping test near Albuquerque, New Mexico. Changes in the water level due to cyclic pumping were accompanied by alternating cycles of compression and expansion of the aquifer system.

A measure of the change in applied stress is the change in water level.



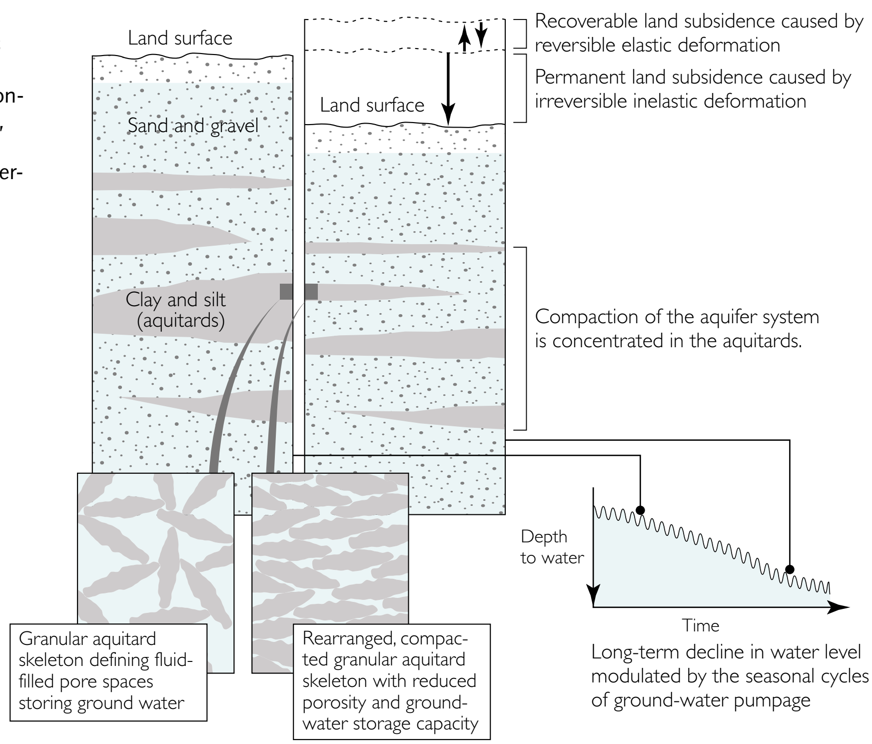
(Heywood, 1997)

fer system, support previously provided by the skeleton is transferred to the fluid and the skeleton expands. In this way, the skeleton alternately undergoes compression and expansion as the pore-fluid pressure fluctuates with aquifer-system discharge and recharge. When the load on the skeleton remains less than any previous maximum load, the fluctuations create only a small elastic deformation of the aquifer system and small displacement of land surface. This fully recoverable deformation occurs in all aquifer systems, commonly resulting in seasonal, reversible displacements in land surface of up to 1 inch or more in response to the seasonal changes in ground-water pumpage.

INELASTIC COMPACTION IRREVERSIBLY ALTERS THE AQUIFER SYSTEM

The maximum level of past stressing of a skeletal element is termed the preconsolidation stress. When the load on the aquitard skeleton exceeds the preconsolidation stress, the aquitard skeleton may undergo significant, permanent rearrangement, resulting in irreversible compaction. Because the skeleton defines the pore structure of the aquitard, this results in a permanent reduction of pore volume as the pore fluid is "squeezed" out of the aquitards into the aquifers. In confined aquifer systems subject to large-scale overdraft, the volume of water derived from irreversible aquitard compaction is essentially equal to the volume of subsidence and can typically range from 10 to 30 percent of the total volume of water pumped. This represents a one-time mining of stored ground water and a small permanent reduction in the storage capacity of the aquifer system.

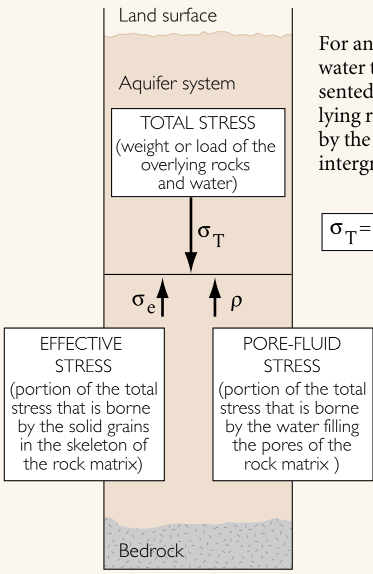
When long-term pumping lowers ground-water levels and raises stresses on the aquitards beyond the preconsolidation-stress thresholds, the aquitards compact and the land surface subsides permanently.



Aquitard Drainage and Aquifer-System Compaction

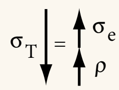
The Principle of Effective Stress

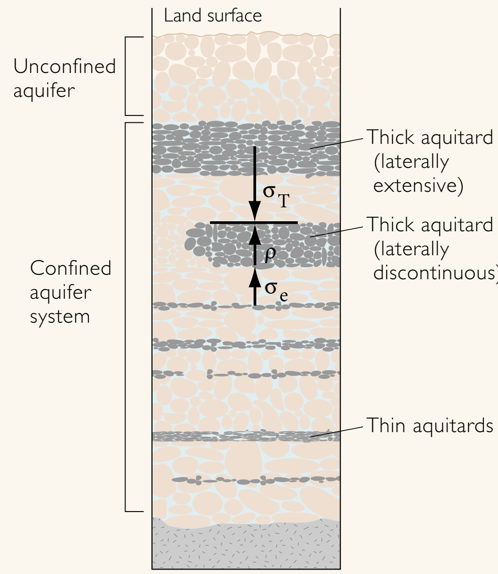
This principle describes the relation between changes in water levels and deformation of the aquifer system.



For any arbitrary plane below the water table, the total stress represented by the weight of the overlying rock and water is balanced by the pore-fluid pressure and the intergranular or effective stress.

$$\boxed{\sigma_T = \sigma_e + \rho}$$



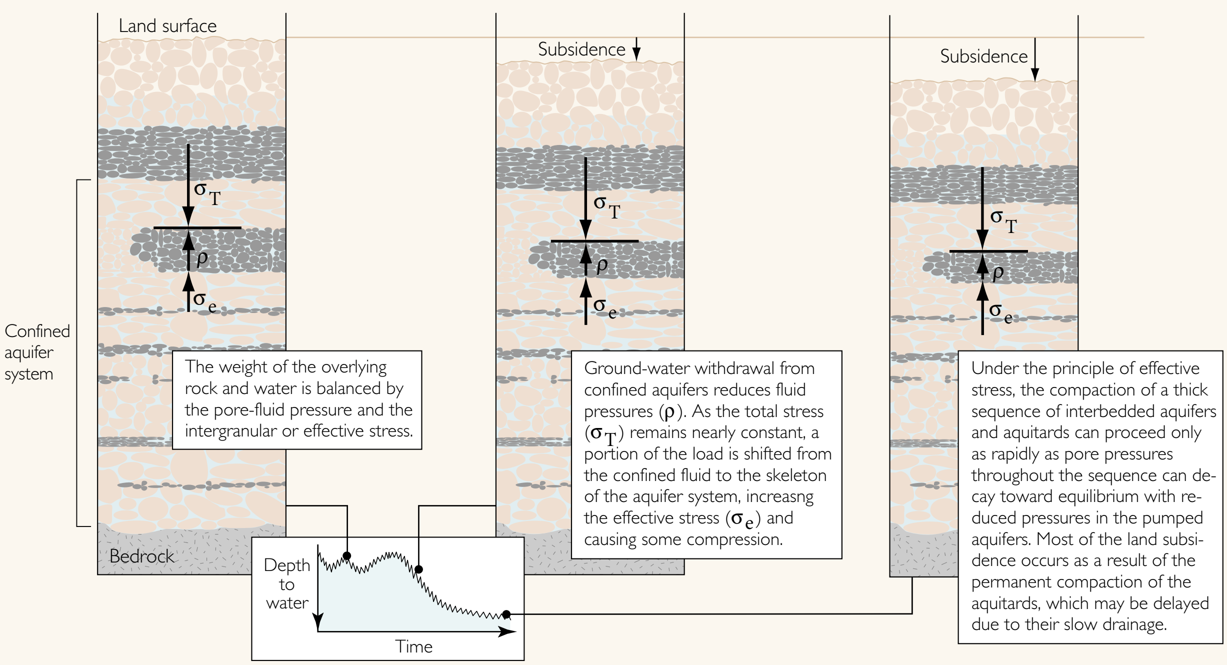


PROLONGED CHANGES IN GROUND-WATER LEVELS INDUCE SUBSIDENCE

Prior to the extensive development of ground-water resources, water levels are relatively stable—though subject to seasonal and longer-term climatic variability.

During development of ground-water resources, water levels decline and land subsidence begins.

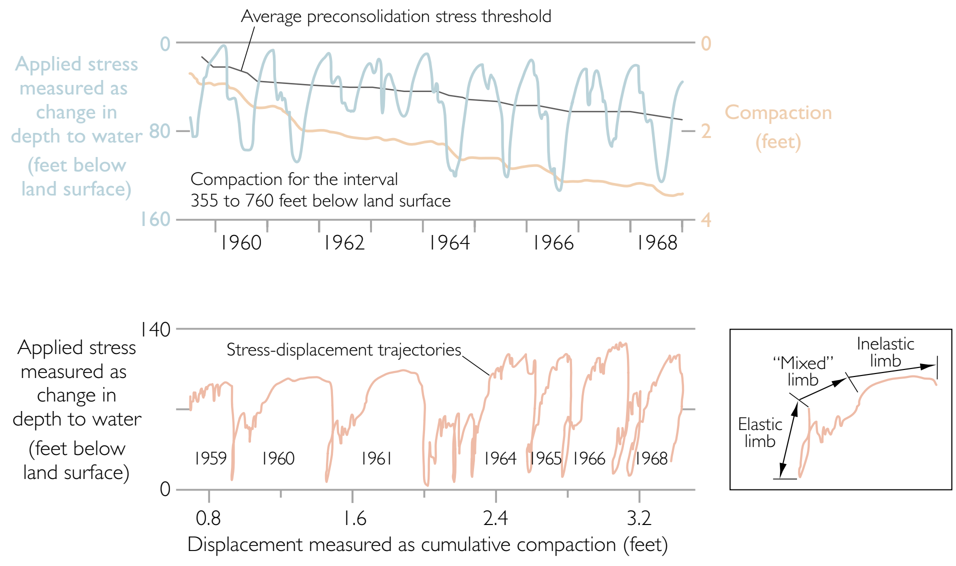
After ground-water pumping slows or decreases, water levels stabilize but land subsidence may continue.



More than 2.5 feet of permanent (inelastic) compaction was observed near Pixley, San Joaquin Valley, California during a 10-year period.

The high summer demand for irrigation water combined with the normally wetter winters causes ground-water levels to fluctuate in response to seasonal pumpage and recharge. The annual cycles of alternating stress increase and decrease are accompanied by cycles of compression and slight expansion of the aquifer system.

Compression proceeds most rapidly when the stress is larger than the preconsolidation stress threshold. Beyond this threshold almost all of the compression is permanent (inelastic) and attributed to the compaction of fine-grained aquitards.



(Riley, 1969)

> *". . . the term **aquitard** has been coined to describe the less-permeable beds in a stratigraphic sequence. These beds may be permeable enough to transmit water in quantities that are significant in the study of regional ground-water flow, but their permeability is not sufficient to allow the completion of production wells within them."*
>
> *—Freeze and Cherry, 1979*

Aquitards play an important role in compaction

In recent decades increasing recognition has been given to the critical role of aquitards in the intermediate and long-term response of alluvial aquifer systems to ground-water pumpage. In many such systems interbedded layers of silts and clays, once dismissed as non-water yielding, comprise the bulk of the ground-water storage capacity of the confined aquifer system! This is by virtue of their substantially greater porosity and compressibility and, in many cases, their greater aggregate thickness compared to the more transmissive, coarser-grained sand and gravel layers.

Because aquitards are by definition much less permeable than aquifers, the vertical drainage of aquitards into adjacent pumped aquifers may proceed very slowly, and thus lag far behind the changing water levels in adjacent aquifers. The duration of a typical irrigation season may allow only a modest fraction of the potential yield from aquitard storage to enter the aquifer system, before pumping ceases for the season and ground-water levels recover in the aquifers. Typically, for thick aquitards, the next cycle of pumping begins before the fluid pressures in the aquitards have equilibrated with the previous cycle. The lagged response within the inner portions of a thick aquitard may be largely isolated from the higher frequency seasonal fluctuations and more influenced by lower frequency, longer-term trends in ground-water levels. Because the migration of increased internal stress into the aquitard accompanies its drainage, as more fluid is squeezed from the interior of the aquitard, larger and larger internal stresses propagate farther into the aquitard.

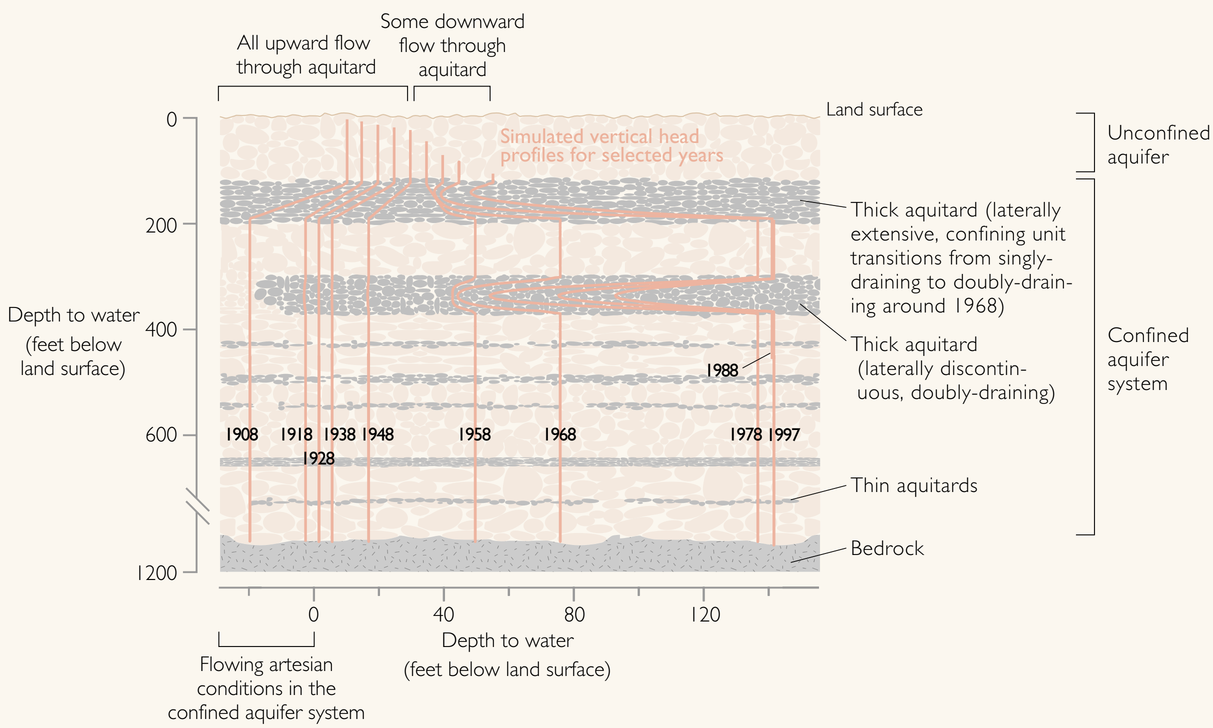
When the internal stresses exceed the preconsolidation stress, the compressibility increases dramatically, typically by a factor of 20 to

Aquitard Drainage and Aquifer-System Compaction

The Theory of Hydrodynamic Consolidation

The theory describes the delay in draining aquitards when water levels are lowered in adjacent aquifers, as well as the residual compaction that may continue long after water levels are initially lowered.

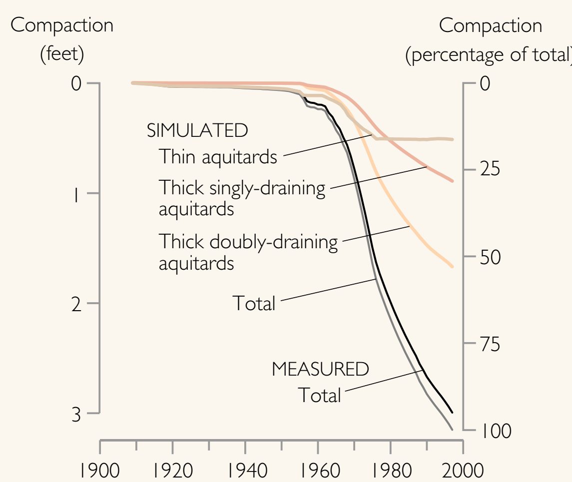
During a 90-year period (1908–1997) of ground-water development in the Antelope Valley, California, the response of water levels in two thick aquitards lags the declining water level in the aquifer. A laterally discontinuous aquitard draining from both upper and lower faces approaches fluid-pressure equilibrium with the adjacent aquifers more rapidly than an overlying laterally extensive aquitard that has a complex drainage history, including a gradient reversal.*



RESIDUAL COMPACTION

Significant amounts of compaction began occurring in the late 1950s after water levels in the aquifers had fallen some 60 feet. Initially, most of the compaction occured in the faster-draining thin aquitards within the aquifers. Subsequently most of the compaction occured in the two thickest and most slowly draining aquitards. Despite stabilization of ground-water levels in the aquifers, more than 0.3 feet of compaction has occurred since 1990, due to residual compaction.

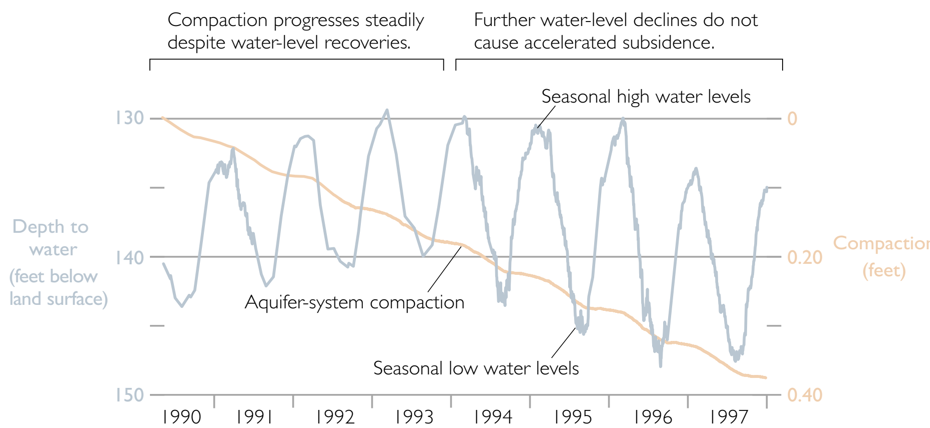
Simulations predict that another 1.3 feet of compaction may ultimately occur even if ground-water levels remain at 1997 levels.



*These results from an aquifer system in Antelope Valley, Mojave Desert, California are based on field measurements and computer simulations of aquitard drainage. They illustrate the history of ground-water-level changes and compaction in the aquifers and aquitards throughout the period of ground-water resource development, 1908-97.

(Michelle Sneed, USGS. written communication, 1998)

100 times, and the resulting compaction is largely nonrecoverable. At stresses greater than the preconsolidation stress, the lag in aquitard drainage increases by comparable factors, and concomitant compaction may require decades or centuries to approach completion. The theory of hydrodynamic consolidation (Terzaghi, 1925)—an essential element of the "aquitard drainage model"—describes the delay involved in draining aquitards when heads are lowered in adjacent aquifers, as well as the residual compaction that may continue long after drawdowns in the aquifers have essentially stabilized. Numerical modeling based on Terzaghi's theory has successfully simulated complex histories of compaction observed in response to measured water-level fluctuations (Helm, 1978).



(Michelle Sneed, USGS, written communication, 1998)

Hydrodynamic lag, which is a delay in the propagation of fluid-pressure changes between the aquifers and aquitards, can be seen at this site in the Antelope Valley, Mojave Desert, California.

The responses to changing water levels following eight decades of ground-water development suggest that stresses directly driving much of the compaction are somewhat insulated from the changing stresses caused by short-term water-level variations in the aquifers.