SIMULATION OF TRANSIENT GROUND-WATER FLOW AND LAND SUBSIDENCE IN THE PICACHO BASIN, CENTRAL ARIZONA

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A numerical model of ground-water flow and land subsidence in a southwest alluvial basin was constructed using the modular finite-difference ground-water flow model (MODFLOW) by McDonald and Harbaugh (1988) to define parameters important to the simulation of land subsidence in alluvial basins and to evaluate the significance of aquifer-system compaction on regional ground-water flow (see Leake abstract for discussion of MODFLOW and the simulation of land subsidence). The Picacho Basin of south-central Arizona was studied because of the magnitude of ground-water pumping stresses and compaction and the availability of compaction and land-subsidence data (see Carpenter abstract for discussion of earth fissures in the Picacho Basin). Simulations included predevelopment conditions in 1887 and transient-flow conditions from 1887 to 1985. The transient-flow conditions are characterized by ground-water withdrawals greatly in excess of natural recharge, storage depletion, hydraulic-head declines of more than 100 m, and land subsidence of as much as 4.5 m.

The compressible part of the aquifer system includes the upper 1,000 m of alluvial deposits that are characterized by interbedded coarse-grained and fine-grained sediments on the basin margin and fine-grained sediments in the basin center (fig. 1). The middle confining bed separates the aquifer system into upper and lower aquifers. This confining bed consists of a thick sequence of fine-grained sediments that include several hundred meters of compressible sediments overlying as much as 2,000 m of relatively incompressible sediments. The difference in compressibility between the upper and lower sediments is inferred from a significant difference in physical properties. Compressible sediments are of low density, 1.9 to 2.2 g/cm^3; high porosity, 0.47 to 0.24 percent; and low seismic velocity, 2.2 to 2.5 km^2. Relatively incompressible sediments are of higher density, 2.2 to 2.5 g/cm^3; lower porosity, less than 0.24 percent; and higher seismic velocities, 2.5 to 4.6 km/s.

Fine-grained beds of various thickness and areal extent are the primary compressible sediments. The occurrence and thickness of individual fine-grained beds increase with depth and from the basin margin toward the basin center where individual beds merge into the middle confining bed. Rates of pore drainage and compaction in compressible fine-grained beds are influenced by bed thickness. One-dimensional simulation of compaction at an extensometer (Epstein, 1987) indicates that drainage of pores in beds that are less than 20 m thick requires less than a few years. Drainage of thicker beds may require decades.

Storage depletion has occurred through dewatering of pores in coarse-grained beds and reduction in pore volume in fine-grained beds. Early pumping was relatively shallow and storage loss occurred primarily through drainage of pore spaces at the water table. Many shallow coarse-grained beds were dewatered as water levels declined. Subsequent deeper pumping below fine-grained beds resulted in responses typical of confined aquifers. Larger hydraulic-head declines resulting from smaller storage coefficients caused the development of large vertical hydraulic gradients, aquifer-system compaction, and a greater significance of reduction in pore volume as a source of water.

A five-layer numerical model was constructed to represent the aquifer system using MODFLOW and a module for simulating aquifer-system compaction, IBS1 (Interbed Storage package #1), by Leake and Prudic (1991). The upper layer represents shallow interbedded alluvial deposits and was simulated as a water-table aquifer with instantaneously draining interbeds. The middle three layers represent the compressible part of the middle confining bed. Layer 2 is the upper 25 m of the confining bed, and layer 3

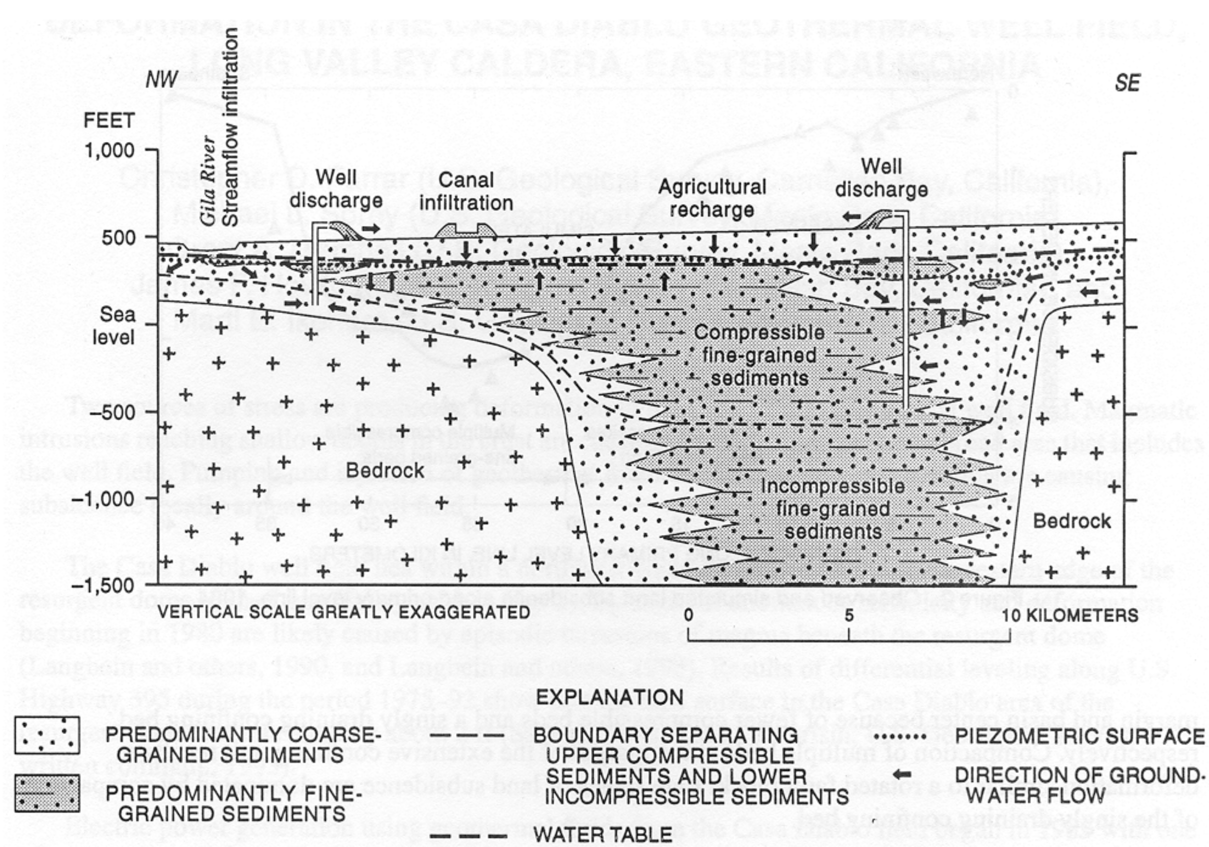

Figure 1. Generalized hydrogeologic section of Picacho Basin showing conceptual transient ground-water flow system.

is the next lower 50 m. Layer 4 is the rest of the compressible sediments in the confining bed. This vertical discretization of the upper part of the confining bed allows simulation of the delayed drainage from the bed. Also, the thickness of layers 1 and 2 represents the thickness of the aquifer system penetrated by a vertical extensometer. Layer 5 represents the lower incompressible confined aquifer.

Mean errors in the simulation of water levels in the upper aquifer system at 14 control points were 4 m throughout the 98 years of simulation, but average absolute errors increased from 5.1 to 19.1 m between simulations of 1950 and 1965 conditions. Most of this error probably is related to delayed drainage of confining beds and vertical hydraulic gradients in the upper layer, both of which were not simulated. The magnitude and sense of the water-level error in later years are similar to standard errors of estimated water levels derived from Kriging analysis and gridding of water-level data. Mean and average absolute land-subsidence errors for simulation of 1984 conditions were 0.17 and 0.30 m, respectively, at 23 bench marks along a primary level line across the main land-subsidence area. Observed land subsidence ranged from 0 to 3.8 m along the level line (fig. 2).

Definition of the thickness and distribution of compressible beds is one of the most important considerations in simulation of compaction in the Picacho Basin. The greatest amount of subsidence is coincident with the greatest number of compressible fine-grained beds that occur at the margin of the middle confining bed (fig. 2). Lesser amounts of compaction and land subsidence occur on the basin

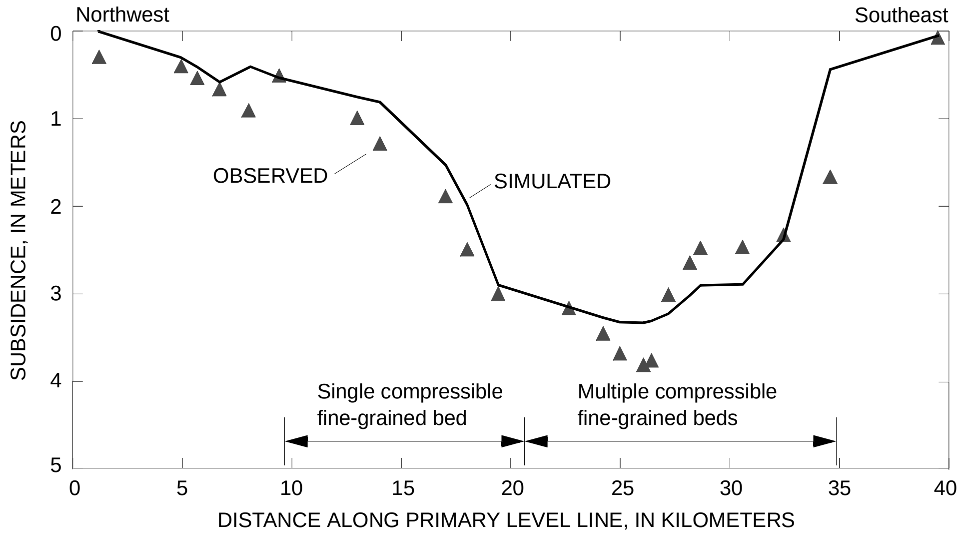

Figure 2. Observed and simulated land subsidence along primary level line, 1984.

margin and basin center because of fewer compressible beds and a singly draining confining bed, respectively. Compaction of multiple beds at the margin of the extensive confining unit results in deformation similar to a rotated fault block. Late stages of land subsidence are dominated by compaction of the singly draining confining bed.

Hydraulic information important to simulation of aquifer-system compaction in the Picacho Basin includes spatial distributions of stress and compaction, specific storage, and vertical hydraulic conductance. Knowledge of stress distributions is useful for model calibration but probably is rare in most basins as in the Picacho Basin. In aquifer systems that include slowly draining confining beds, spatial distributions of compaction are needed to calibrate storage properties and vertical hydraulic conductance. The vertical distribution of compaction can be monitored with partially penetrating vertical extensometers and Global Positioning System surveys of land subsidence. Vertical-extensometer data also are useful in establishing representative specific storage and vertical hydraulic-conductance values. A history of land-subsidence distributions alone is inadequate for calibration of storage properties and vertical hydraulic conductance in aquifer systems such as the Picacho Basin.

Results of model simulations indicate that release of water from storage in fine-grained beds became an increasingly significant source of water as development occurred. Most of the water budget for the transient-flow period is dominated by ground-water withdrawal for agriculture, storage depletion through pore drainage, and agricultural recharge. However, rates of water released through reduction in pore volume are similar in magnitude to flow rates at head-dependent boundaries and rates of natural recharge. Reduction in pore volume represents about 10 percent of storage depletion during mid-stages of development and as much as 25 percent during late stages of development.