Piezometric-Extensometric Estimations of Specific Storage in the Albuquerque Basin, New Mexico

By Charles E. Heywood

Appropriate values of skeletal specific storage (S_{sk}) and hydraulic conductivity are required for numerical simulations to achieve useful predictions of ground-water level responses to future pumping. These parameters often are estimated from the measured hydraulic response to short-duration pumping tests, which may effectively stress only the more permeable parts of the aquifer system within a previously stressed magnitude range. Because the magnitude of S_{sk} may depend on the time period of the applied hydraulic stress as well as the stress history of the aquifer system (Helm, 1976; Galloway, 1995), estimates of S_{sk} from such tests often are applied inappropriately in ground-water flow simulations for systems with significant low-permeability lithologies or a component of inelastic compressibility.

Early in a test close to the pumped well, horizontal strain of the aquifer matrix may induce appreciable pore-pressure changes before the hydraulic propagation of drawdown. Such effects were observed in the test described in this paper. Analytical solutions of radial ground-water flow problems are most sensitive to the storage coefficient (S) during early time and typically are based on models that neglect horizontal strain. If piezometric data close to the pumped well are analyzed with such a model, erroneous parameter estimates may result. For these reasons, direct in-situ measurement of vertical aquifer-system matrix compressibility is preferable for estimating aquifer-system specific storage.

In the Albuquerque Basin of New Mexico, ground-water withdrawals result in depletion of aquifer-system storage and of surface-water flow in the Rio Grande. Because the economics and administration of these water sources differ, an improved understanding of ground-water and surface-water interaction near the Rio Grande was desired, and an aquifer test was carried out during the winter of 1995. A 3-month recovery period preceded 54 days of pumping at about 147 L/s, which was followed by a 1-month recovery period. The production well was screened from 71 to 244 m; however, post-test televiewing and flow-metering revealed that the screen was encrusted and did not produce significant water below 195 m (Condé Thorn, hydrologist, U.S. Geological Survey, oral commun., 1995).

Before the test in the fall of 1994, a 315-meter borehole extensometer was installed 378 m from the test well as part of an effort to monitor aquifer-system compaction that would result in land subsidence. This counter-weighted borehole-pipe extensometer design followed guidelines described by Riley (1984) to achieve high-strain sensitivity. A precision transducer measures vertical displacements with a resolution of several microns corresponding to a vertical-strain sensitivity of 10^{-8}. A nest of four piezometers was installed 5 m from the extensometer and equipped with transducers capable of detecting 2 mm of water-level change. During the aquifer test, water levels also were recorded in three shallower piezometers approximately 80 m from the extensometer and in 12 other observation wells at various distances farther from the pumped well. The electrical-resistivity borehole-geophysical log illustrates the depth and thickness of sand and clay interbeds of the aquifer-system interval penetrated by the extensometer (fig. 1). Clay and silt layers correlate with lower resistivity. Piezometer screens were placed in high-resistivity intervals that were assumed to be sands of high permeability.

The relation between aquifer pore-pressure decrease and vertical strain for the period of drawdown and subsequent recovery is shown in figure 2. Pore pressure was measured 6 m from the

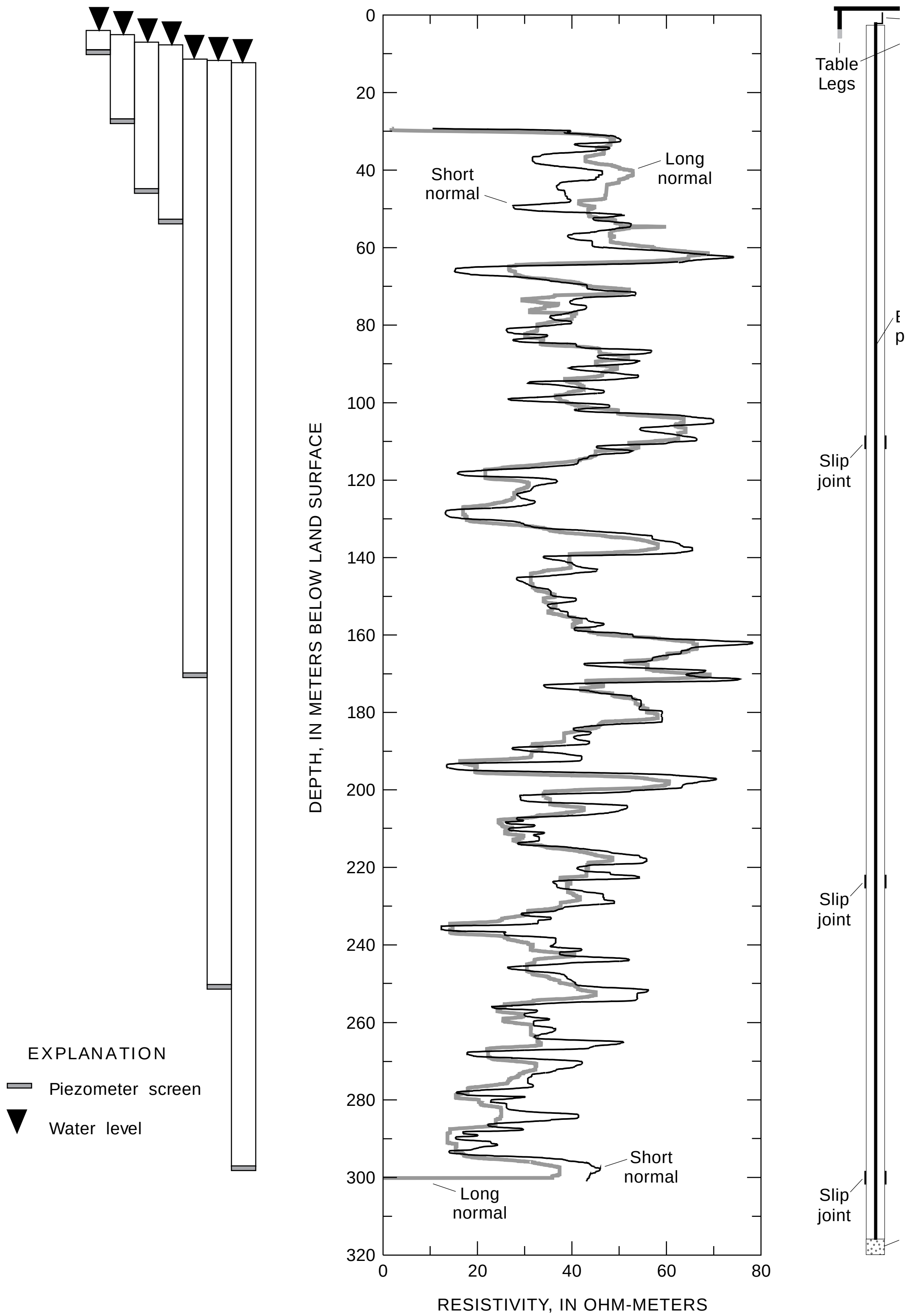

Figure 1. Summary of Montaño extensometer-piezometer installation.

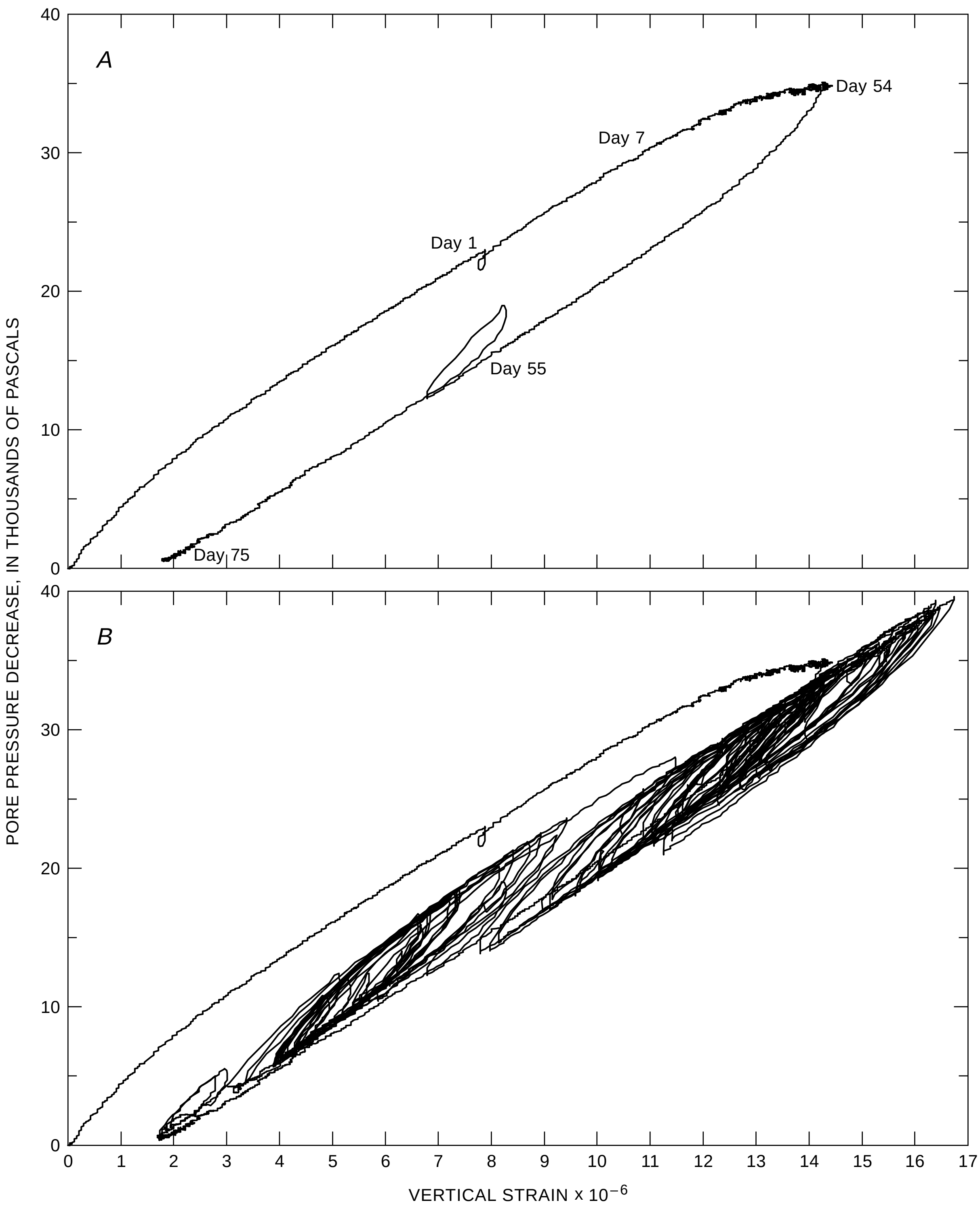

Figure 2. Pore-pressure change at a depth of 171 meters compared to aquifer-system strain. *A*, Test-pumping and recovery period. *B*, Test-pumping and recovery period and subsequent period of uncontrolled pumping at multiple wells.

extensometer at a depth of 171 m, and vertical strain was measured over the interval of the extensometer (fig. 1). A 27-minute pump failure that occurred 1 day into the aquifer test caused measurable elastic recovery at the extensometer and resulted in a small loop in the plot. An analogous effect was observed on day 55 when the pumped well was inadvertently turned back on for about 2 hours. Piezometer hydrographs flattened approximately 1 week into the drawdown and recovery periods of the test and indicate that drawdown approached steady state in permeable parts of the aquifer system where piezometers were screened. As shown in figure 2*A*, the flatter slope from day 7 to day 54 probably reflects compaction of interbedded sediments of low permeability as they slowly drained excess pore pressure to the surrounding aquifer. This decrease in slope also may be due to apparent strain attributable to uncompensated long-period temperature effects in the extensometer apparatus. The controlled-test data from figure 2*A* and an additional 60 days of superimposed post-test data are shown in figure 2*B*. During the latter 60 days, normal "uncontrolled" pumping from multiple wells near the extensometer resulted in many drawdowns of various magnitudes on a daily basis. The stress-strain plot during this period is shifted to the right of the plot for the controlled test suggesting that (1) some inelastic compaction resulted from the test, (2) an uncompensated temperature effect on the extensometer has resulted in apparent strain, or (3) the recovery period was 39 percent of the drawdown period, which was insufficient for the pore pressure in less permeable parts of the aquifer system (above or below the piezometer screened at 171 m) to return to prepumping levels. Since the late 1950's, production wells near the extensometer generated approximately diurnal drawdowns of a similar magnitude to drawdowns generated in the aquifer test; however, it is possible that the aquifer system has not experienced that magnitude of constant drawdown for a period as long as the aquifer test (54 days). During the aquifer test, the middle of the thick interbeds of low permeability may have had more time to drain excess pore pressure than at any previous time resulting in effective stress magnitudes above a preconsolidation level in the middle of the interbeds. Resulting inelastic compaction totaling 0.45 mm would generate the apparent inelastic strain shown in figure 2*B*. Additional seasonal stress-strain and temperature data will enable discrimination of these three possibilities for the right shift of the stress-strain plot.

Riley (1969) demonstrated the utility of similar stress-strain plots for determining elastic- and inelastic-storage coefficients. The magnitude of the inverse slope of this stress-strain plot would be a measure of the compressibility of the average aquifer matrix over the interval spanned by the extensometer if the change in pore pressure were uniform in that interval. The distribution of aquifer-system pore-pressure change was sampled with piezometers over seven depth intervals. Sample hydrographs, in conjunction with the vertical-permeability distribution inferred from the borehole-resistivity log, were used to estimate the change in vertical pore-pressure distribution during the aquifer test. The average pore-pressure change over the sampled aquifer-system interval was approximated by the average drawdown recorded in the four deepest piezometers. For the aquifer-system interval spanned by the extensometer, the resulting estimated matrix compressibility, α, is 5×10^{-10} Pa^{-1}. For an average matrix porosity, n, of 0.3 and water compressibility, β, of 4.4×10^{-10} Pa^{-1}, the corresponding specific storage, S_s, $[\rho g(\alpha+n\beta)]$ is 7×10^{-6} m^{-1}, where the weight density of water, ρg, is 9,800 kg m^{-2} s^{-2}.

The shallowest piezometer near the extensometer was screened across the water table. During the pumping period of the test, the water-table elevation recorded in this well declined less than 0.3 m. Assuming a specific yield of 0.2, the resulting decrease in geostatic stress on underlying sediments was less than 6×10^2 Pa. Measured pore pressure decreased by 3.6×10^4 Pa in the piezometer at a depth of 171 m and by somewhat less in the piezometers screened at other depths. For sediments in the producing aquifer interval (from a depth of approximately 60 to 200 m), the magnitude of decreased effective stress resulting from water-table lowering, therefore, was on the order of 2 percent of the increased effective stress due to decreased pore pressure. Because the effect of water-table lowering on effective stress at depth generally was minor during the aquifer test, the water table was assumed to be static. A unit decrease in measured pore pressure, therefore, corresponded to a unit increase in effective stress.

Piezometric responses to earth tides enabled an independent estimation of specific storages of the aquifer sands surrounding each piezometer screen. Three 3-week series of hourly pressure data were filtered to pass frequencies between 0.8 and 3.0 cycles/d by a digital 9th order elliptic filter with 0.01 decibels of ripple in the passband and a stop band that was 100 decibels lower than the peak value in the passband. The theoretical magnitude of volumetric strain due to earth tides was calculated from tidal theory (Harrison, 1971) assuming a Poisson ratio of 0.25. The magnitudes of aquifer volumetric strain and resulting piezometric responses at six principal tidal frequencies were determined by Fourier regression from which values of S_s were calculated for the M2 and O1 frequencies by assuming grain incompressibility (Bredehoeft, 1967). Figure 3 shows the mean S_s calculated from the M2 tidal response compared to screen depth for the four deepest piezometers adjacent to the extensometer (darker circles and lines). Error-bar widths are 2 standard deviations. These values of S_s are smaller than that of the aggregate aquifer system and suggest that aquifer sands are stiffer than the aquifer system, which includes interbedded clay aquitards. The data suggest that sand-matrix compressibility decreases approximately linearly with increasing overburden stress. Open circles representing a similar analysis (Heywood, 1995) of two piezometers in a similar setting in El Paso, Texas, follow a similar trend. Barometric efficiency (BE) was estimated as a function of frequency (Rojstaczer, 1988) for the Albuquerque piezometers and was found to be about 0.2 in the tidal-frequency range. This magnitude of BE and estimated S_s suggests sand-matrix porosities of about 0.3. The flat frequency response in the tidal spectrum suggests that piezometric earth-tide responses probably are not significantly attenuated by pressure diffusion.

REFERENCES CITED

Bredehoeft, J.D., 1967, Response of well-aquifer systems to earth tides: American Geophysical Union, Journal of Geophysical Research, v. 72, no. 12, p. 3075–3087.

Galloway, D.L., 1995, The frequency dependence of aquifer-system elastic storage coefficients—Implications for estimates of aquifer hydraulic

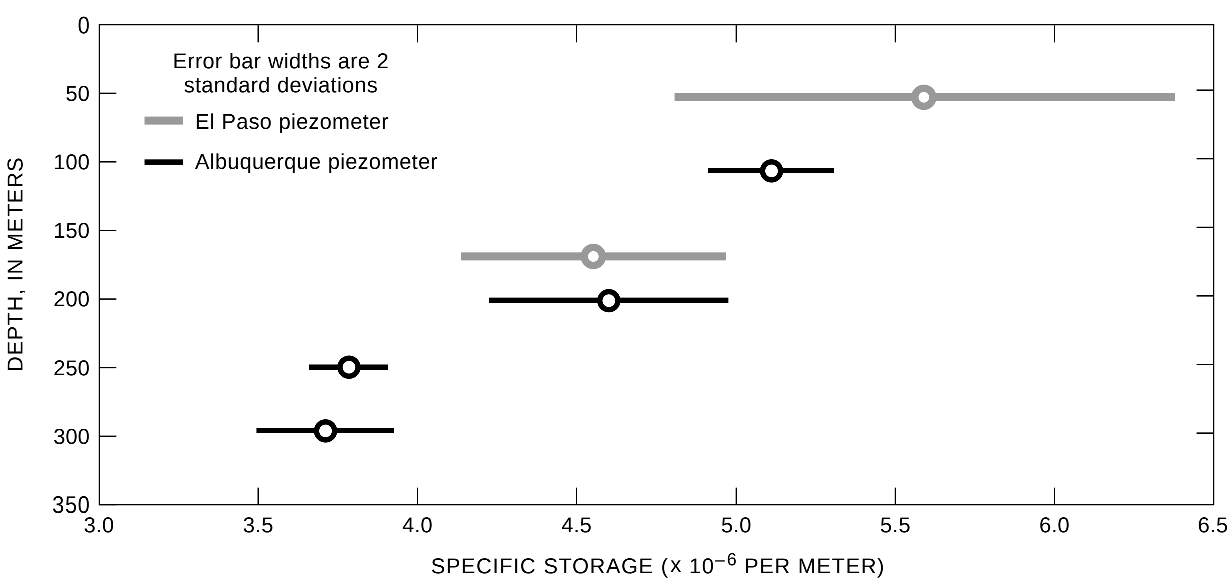

Figure 3. Specific storage for aquifer sands in Rio Grande alluvium from M2 tidal response.

properties and aquifer-system compaction, *in* Prince, K.R., Galloway, D.L., and Leake, S.A., eds., U.S. Geological Survey Subsidence Interest Group Conference, Edwards Air Force Base, Antelope Valley, California, November 18–19, 1992—Abstracts and Summary: U.S. Geological Survey Open-File Report 94–532, 84 p.

Harrison, D.H., 1971, New computer programs for the calculation of earth tides: Boulder, University of Colorado, Cooperative Institute for Research in Environmental Sciences.

Helm, D.C., 1976, One-dimensional simulation of aquifer system compaction near Pixley, California 2.—Stress dependent parameters: American Geophysical Union, Water Resources Research, v. 12, no. 3, p. 375–391.

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

Riley, F.S., 1969, Analysis of borehole extensometer data from central California, *in* Tison, L.J., Land Subsidence: International Association of Hydrological Sciences Publication 89, v. 2, p. 423–431.

__ 1984, Developments in borehole extensometry, *in* Johnson, A.I., Carbognin, L., and Ubertini, L., eds, Land Subsidence: International Association of Hydrological Sciences Publication 151, p. 169–186.

Rojstaczer, S.A., 1988, Determination of fluid flow properties from the response of water wells to atmospheric loading: American Geophysical Union, Water Resources Research, v. 24, no. 11, p. 1927–1938.