Summary of Extensometric Measurements in El Paso, Texas

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 03-4158

Prepared in cooperation with the
INTERNATIONAL BOUNDARY AND WATER COMMISSION,
UNITED STATES SECTION

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Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Altitude, as used in this report, refers to distance above or below sea level.

SUMMARY OF EXTENSOMETRIC MEASUREMENTS IN EL PASO, TEXAS

By Charles E. Heywood

ABSTRACT

Two counter-weighted-pipe borehole extensometers were installed on the left bank of the Rio Grande between El Paso, Texas, and Ciudad Juarez, Chihuahua, Mexico, in 1992. A shallow extensometer measures vertical compaction in the 6- to 100-meter aquifer-system depth interval. A deep extensometer measures vertical compaction in the 6- to 305-meter aquifer-system depth interval. Both extensometers are referenced to the same surface datum, which allows time-series differencing to determine vertical compaction in the depth interval between 100 and 305 meters. From April 2, 1993, through June 13, 2002, 1.6 centimeters of compaction occurred in the 6- to 305-m depth interval. Until February 1999, most aquifer-system compaction occurred in the deeper aquifer-system interval between 100 and 305 meters, from which ground water was extracted. After that time, compaction in the shallow interval from 6 to 100 meters was predominant and attained a maximum of 7.6 millimeters by June 13, 2002. Minor residual compaction is expected to continue; continued maintenance of the El Paso extensometers would document this process.

INTRODUCTION

Concerns about potential land subsidence associated with changes to the surface-water delivery system in the Rio Grande Valley in El Paso, Texas (fig. 1), were summarized by Land and Armstrong (1985). A primary concern was the potential for increased land subsidence in the area of a proposed extension to the American Canal, which is adjacent to areas of substantial ground-water withdrawals by the cities of El Paso, Texas, and Juarez, Mexico. Seepage to the underlying aquifer system in the El Paso-Juarez area reduces flow in the Rio Grande. Salvaging surface-water flow by diverting it from the Rio Grande into the American Canal Extension (ACE) might decrease aquifer-system recharge in this area, exacerbating ground-water decline. Subsidence in this area could be caused either by compaction in the interval (approximately 100 to 200 m below land surface) from which ground water is extracted or by compaction in a shallower aquifer interval that is more hydraulically connected to the Rio Grande. A decrease or cessation of flow in the Rio Grande would cause the local water table to decline and possibly cause compaction in the shallow parts of the aquifer system. To distinguish between these two components of land-surface subsidence, two vertical extensometers were installed adjacent to the Rio Grande downstream from the terminus of the original American Canal. The monitoring site was selected at the location of probable maximum hydrologic effects from construction of the ACE rather than at the location of maximum subsidence (probably north of the Rio Grande Valley near areas of maximum ground-water drawdown). About 4 years of preliminary compaction data were obtained while the ACE was being constructed. Flow diversion from the Rio Grande into the western section of the ACE began on February 15, 1997; the entire length of the ACE was operational by February 1999 (Rong Kuo, U.S. International Boundary and Water Commission, oral commun., 2002).

This report was prepared in cooperation with the International Boundary and Water Commission, United States Section. The report documents extensometric measurements made adjacent to the Rio Grande in El Paso, Texas, between April 2, 1993, and June 13, 2002. Although water levels were measured at seven depth intervals over this period, these data are not included in this report but are stored in the U.S. Geological Survey (USGS) National Water Information System database. The extensometers are very sensitive to vertical aquifer-system strain and have recorded seismic surface waves (Heywood, 2000). The use of El Paso extensometric and piezometric data to determine aquifer-system compressibility has been documented (Heywood, 1995) and is not discussed in this report.

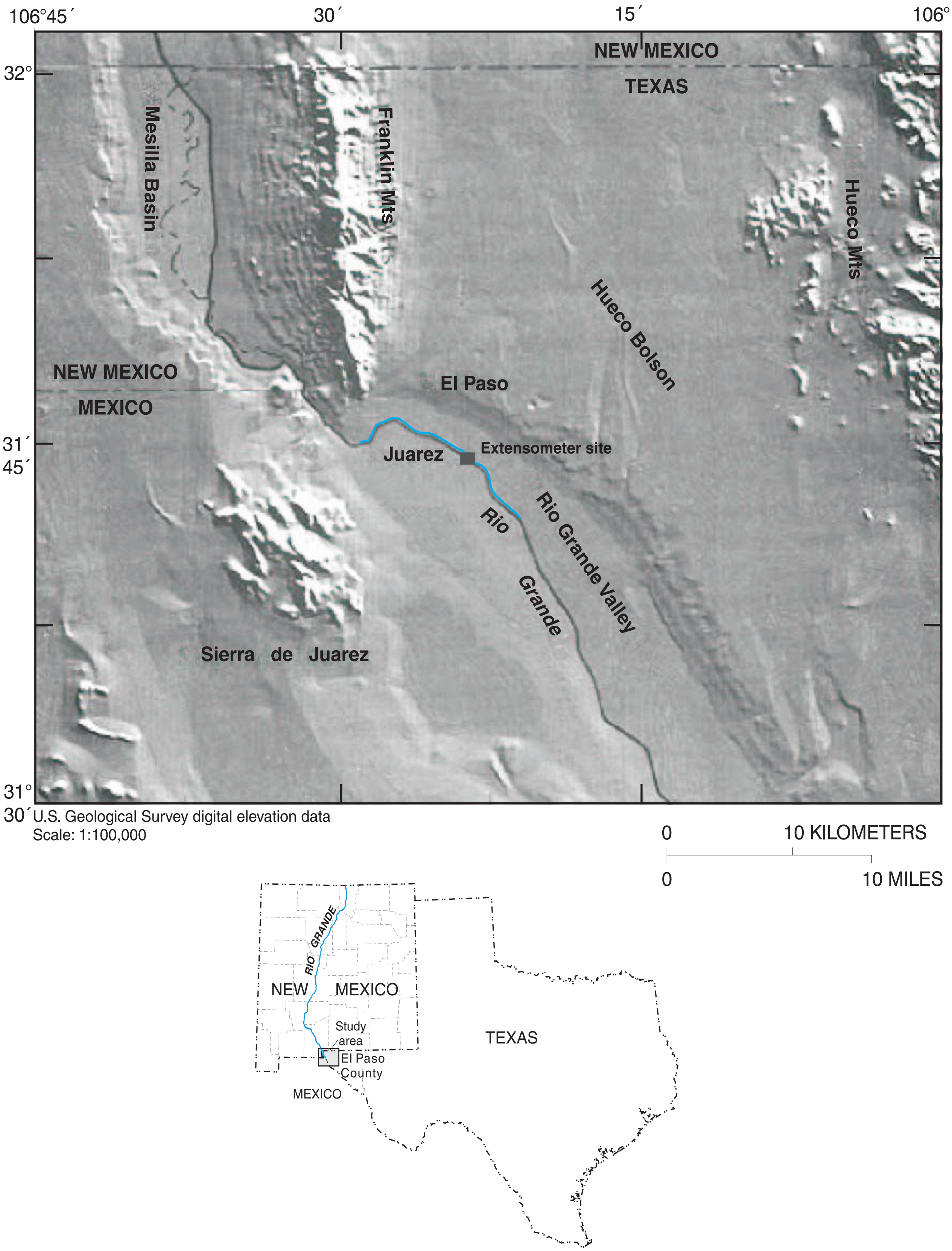

Figure 1. Shaded relief map of southern Hueco Bolson showing location of extensometer site near El Paso, Texas, and Ciudad Juarez, Chihuahua, Mexico. American Canal and American Canal extension shown in blue.

METHODS

In the summer and fall of 1992, two vertical borehole extensometers were installed adjacent to the Rio Grande in El Paso, Texas, at latitude 31° 44’ 35” N., longitude 106° 23’ 57" W. (fig. 1). A shallow extensometer was completed to a depth of 100 m, which is just above the interval of water production in wells in the Rio Grande Valley. A deep extensometer was completed to a depth of 340 m in low-permeability clay underlying the freshwater-producing interval of the Hueco aquifer system. The construction and depth intervals of each extensometer, short- and long-normal electrical resistivity logs of the deep extensometer borehole, and the potentiometric heads in the screened intervals of piezometers adjacent to the extensometers are shown in figure 2.

Sandy parts of the aquifer system, presumed to be relatively permeable, correlate with the higher resistivity depth intervals on the resistivity log. Zones in which low-permeability clays were cored correlate with lower resistivity depth intervals on the resistivity log. The clay zones are, in places, more than 10 m thick (fig. 2).

Vertical displacement of both extensometer pipes was measured with respect to the same datum by use of a datum table in the extensometer shelter (fig. 3). The three legs of the datum table are each thermally insulated and mechanically isolated from surrounding alluvium to a depth of 6 m, where they are anchored in cement. The extensometers therefore measure aquifer-system compaction in the intervals from 6 to 100 m and from 6 to 340 m. By subtracting the shallow extensometer data from the deep extensometer data, a record was obtained of aquifer-system compaction in the 100- to 340-m interval. This depth interval includes the freshwater-producing interval of the Hueco aquifer system in the Rio Grande Valley in which water production wells are screened.

Temperature variations can cause the metal extensometer components to change length, thereby creating an apparent displacement that is noise to the signal of interest. Five thermistor sensors were installed at various points on the extensometer apparatus to monitor temperature variations and their correlation to the displacement signals. The amplitude of the diurnal temperature variations changed with the seasons and was typically less than 0.07 mm. Because the extensometer pipes and table legs were components with comparable thermal expansion in a similar temperature environment, the temperature effects in each were of similar amplitude and phase. Temperature effects are relatively insignificant in the 100- to 340-m compaction record because the compaction time series for the 100- to 340-m depth interval was obtained by calculating the difference between the deep and shallow extensometer displacement time series.

Riley (1969) discussed the desirability of minimizing frictional contact between an extensometer pipe and the surrounding borehole casing in order to accurately measure aquifer-system compaction. Compaction not measured because of either static (stick-slip) or sliding friction is termed "frictional dead band." During final assembly of the extensometric apparatus, the optimal counter weight for each extensometer pipe was determined by measuring and minimizing frictional dead band.

A precision digital barometer monitored changes in atmospheric pressure to determine barometric effects in the piezometers. The atmosphere exerts a buoyant force on the extensometer counter weights and lever arms, which in turn exerts a tensile stress on the extensometer pipes. The effect of a reasonable range of barometric pressure on extensometer pipe length was calculated and determined to be negligible.

The displacement of each extensometer pipe with respect to the surface datum table was measured with three instruments: (1) a dial gage with 5-micrometer (0.0002-in.) resolution, (2) a 100-mm linear displacement transducer with 10-micrometer (0.0004-in.) resolution, and (3) an analog strip-chart recorder (modified for 13X amplification and 96-day chart duration) with 30-micrometer (0.001-in.) resolution. The dial gages were used to calibrate the displacement measured with the transducers and strip-chart recorders. The configuration of one transducer and dial gage located between the shallow extensometer pipe and datum table is shown in figure 3.

Dial-Gage Data

Both dial-gage measurements were recorded when the extensometer site was visited and when analog strip charts were replaced. These measurements and the displacement since April 2, 1993, are summarized in table 1.

Strip-Chart Recorder Data

An analog water-level recorder provided a continuous analog record of displacement for each extensometer. A custom counter weight provided

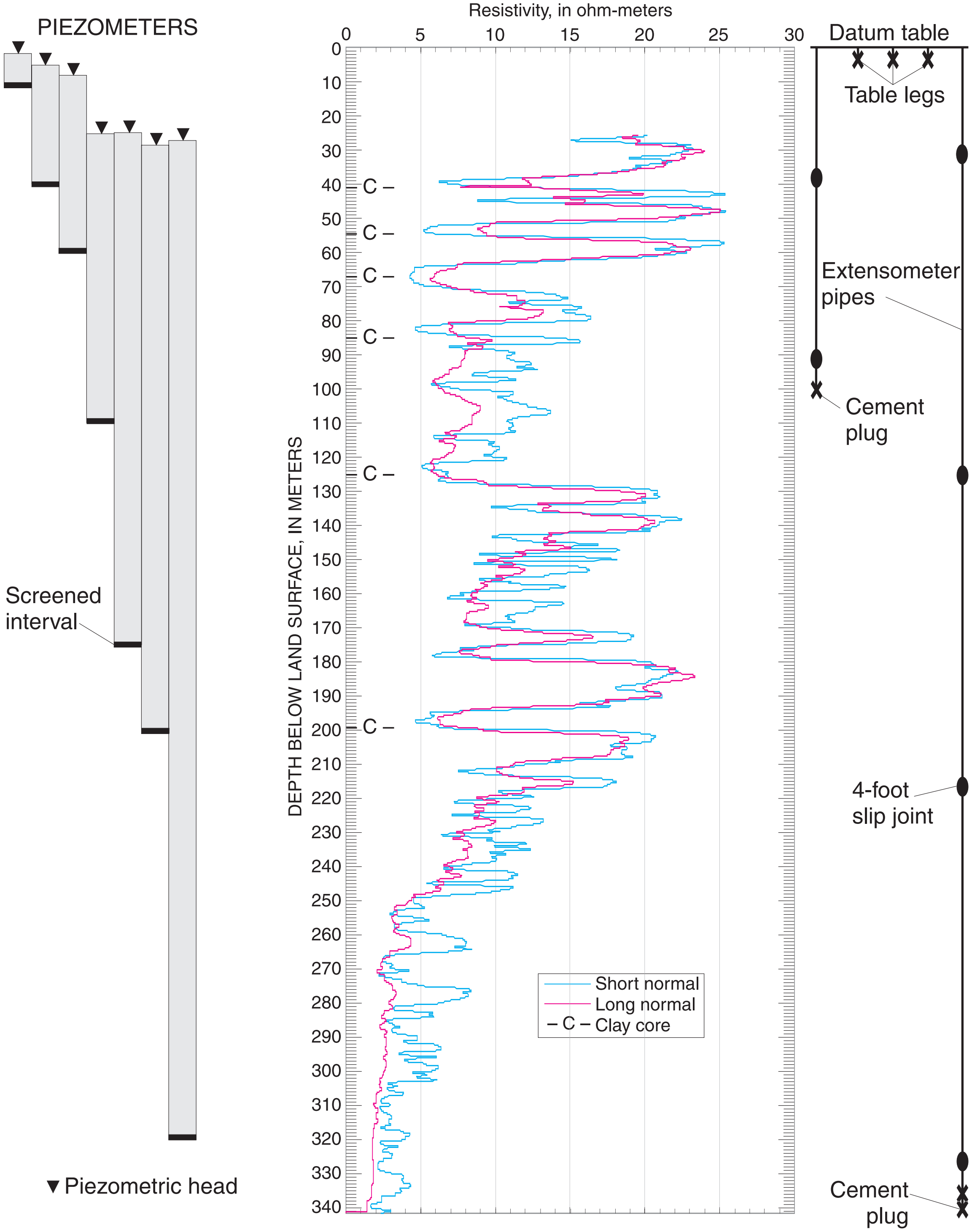

Figure 2. Hydrogeologic summary of borehole electrical resistivity logs, intervals of selected core samples collected at the extensometer site, and water levels measured in piezometers on November 16, 1992.

Figure 3. Photograph of shallow extensometer lever arm, datum table, and selected associated instruments.

Table 1. Dial-gage readings on deep and shallow extensometers

Date	Greenwich mean time	Dial-gage reading for deep extensometer (inches)	Displacement (millimeters)	Dial-gage reading for shallow extensometer (inches)	Displacement (millimeters)
4/2/1993	2330	0.6171	0.000	0.4447	0.000
5/5/1993	0130	0.6680	1.293	0.4631	0.467
6/3/1993	1618	0.6804	1.608	0.4666	0.556
6/4/1993	1304	0.6835	1.687	0.4680	0.592
6/24/1993	2131	0.6658	1.237	0.4561	0.290
6/25/1993	1329	0.6655	1.229	0.4591	0.366
6/25/1993	1600	0.6659	1.240	0.4623	0.447
8/9/1993	2200	0.6189	0.046	0.4481	0.086
8/10/1993	1330	0.6160	-0.028	0.4487	0.102
10/20/1993	1604	0.5859	-0.792	0.4441	-0.015
11/4/1993	1647	0.5992	-0.455	0.4504	0.145
1/13/1994	2032	0.6267	0.244	0.4762	0.800
1/14/1994	2132	0.6275	0.264	0.4766	0.810
4/19/1994	2200	No data	No data	0.4502	0.140
4/20/1994	1452	No data	No data	0.4488	0.104

Table 1. Dial-gage readings on deep and shallow extensometers--Concluded

Date	Greenwich mean time	Dial-gage reading for deep extensometer (inches)	Displace-ment (millimeters)	Dial-gage reading for shallow extensometer (inches)	Displacement (millimeters)
5/17/1994	2000	0.5909	-0.665	0.4871	1.077
8/5/1994	1540	0.5992	-0.455	0.4682	0.597
9/13/1994	2008	0.5951	-0.559	0.4632	0.470
9/14/1994	2033	0.6019	-0.386	0.4651	0.518
9/15/1994	1425	0.6043	-0.325	0.4649	0.513
12/1/1994	2338	0.6784	1.557	0.4871	1.077
12/2/1994	1502	0.6774	1.532	0.4868	1.069
1/12/1995	2027	0.6861	1.753	0.4998	1.400
3/7/1995	1651	0.7076	2.299	0.4890	1.125
6/6/1995	1541	0.7079	2.306	0.4742	0.749
9/6/1995	1930	0.7213	2.647	0.4632	0.470
9/25/1995	1630	0.6660	1.242	0.4490	0.109
10/26/1995	1819	0.6568	1.008	0.4481	0.086
1/31/1996	1752	0.6799	1.595	0.4559	0.284
3/7/1996	2357	0.7016	2.146	0.4642	0.495
6/11/1996	1545	0.8156	5.042	0.4709	0.665
11/19/1996	1438	0.7923	4.450	0.4471	0.061
5/30/1997	1537	0.7835	4.227	0.4656	0.531
5/27/1998	No data	No data	No data	0.4850	1.024
3/3/1998	No data	No data	No data	0.4628	0.460
5/19/1999	No data	No data	No data	0.5562	2.832
11/5/1999	1942	No data	No data	0.5128	1.730
11/5/1999	2000	No data	No data	0.5141	1.763
2/9/2000	2056	0.9618	8.755	0.5483	2.631
2/9/2000	2125	0.9618	8.755	0.5545	2.789
5/4/2000	2108	1.0520	11.046	0.6369	4.882
7/27/2000	1724	1.1249	12.898	0.6440	5.062
10/18/2000	1955	1.1100	12.520	0.5978	3.889
1/19/2001	1840	1.0921	12.065	0.6009	3.967
6/21/2001	2100	1.1839	14.397	0.6962	6.388
9/25/2001	2123	1.1340	13.129	0.6321	4.760
9/25/2001	2134	1.1340	13.129	0.6303	4.714
12/13/2001	2050	1.1389	13.254	0.6492	5.194
12/13/2001	2100	1.1389	13.254	0.6490	5.189
3/19/2002	2115	1.1611	13.818	0.7120	6.789
6/13/2002	1600	1.2338	15.664	0.7500	7.755

torque on the recorder drum to prevent dead band from gear backlash. From April 2 to June 24, 1993, the strip-chart clock-motor gear was set so that one chart encompassed a 32-day period. The drive-gear assembly was then further modified to increase the chart time span to 96 days. A field visit to the extensometer site was scheduled approximately every 3 months to replace charts and download digital data. A complete analog record of extensometer displacement from April 2, 1993, to March 15, 2002, has been recorded on 82 paper charts (41 for each extensometer), which are archived at the USGS office in Albuquerque, New Mexico.

Digital Data

Zero displacement values were assigned to the beginning of the digital and analog record at 17:30 Greenwich mean time on April 2, 1993; displacement data were measured from these initial positions. The vertical displacement of each extensometer pipe was recorded every 30 minutes with the displacement transducer and digital data logger. The ratiometric resistance of each transducer in an AC Half Bridge configuration was an analog for displacement. The digital data logger provided 2,500-millivolt excitation for two single-ended measurements with opposite polarity for ion depolarization. The measurement was recorded on a digital storage module. Dial-gage readings (table 1) and corresponding transducer measurements were fit with linear least-squares regression to obtain a conversion factor for translating the ratiometric transducer output to vertical displacement. The displacement transducers have a nominal 10-cm (4-in.) range. The regression fit of transducer output to dial-gage measurement of extensometer displacement for the deep extensometer is shown in figure 4. The slope of the regression line is -3.8928, the y intercept is 2.4433, and the coefficient of determination (r^2) is 0.99956. Because of several malfunctions, the fit of transducer data from the shallow extensometer to all dial-gage readings (table 1) was poor. The strip-chart records for the shallow extensometer were digitized for problematic periods.

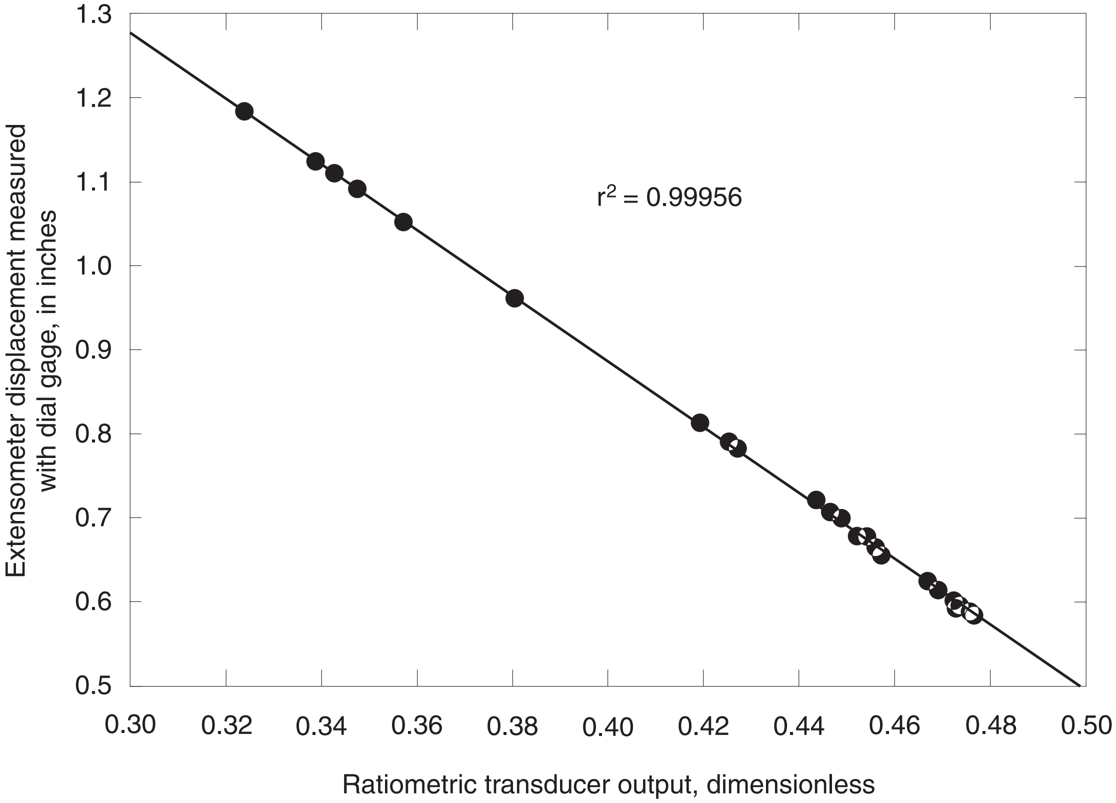

Figure 4. Regression fit of transducer output and deep extensometer displacement.

After the raw digital transducer output was downloaded, the data were converted to vertical displacements (in millimeters) and smoothed with a 24-hour moving average filter to remove the small diurnal temperature effects. The 30-minute data were then resampled at a daily interval (fig. 5). Calculating the difference between the shallow and deep extensometer displacement time series yielded a measure of compaction in the aquifer-system interval between 100 and 340 m deep (fig. 6).

EXTENSOMETRIC MEASUREMENTS

From April 1993 through January 1999, minor (less than 1 mm) compaction occurred within the 6- to 100-m aquifer-system interval spanned by the shallow extensometer (fig. 5). The similarity of the total compaction record (6 to 340 m) to the compaction record in the deeper (100 to 340 m) aquifer-system interval (fig. 6) indicates that most aquifer-system compaction occurred in the deeper interval from April 1993 through January 1999. Ground-water withdrawals within the United States part of the Rio Grande Valley decreased after 1995 because of increased chloride concentration in production wells (Heywood and Yager, 2003). The consequent decreased change in ground-water-level variations is evident as decreased amplitude of monthly and seasonal compaction variations in the deep compaction record (fig. 6).

From February 1999 through the end of the record in June 2002, 6.7 mm of net compaction occurred in the shallow aquifer-system interval, with seasonal elastic rebound during the winter months. Compaction in the deep aquifer-system interval appears to have continued until August 2000, then abated or recovered somewhat. Possibly decreased total geostatic stress resulting from the declining water table has compensated for decreased aquifer-system pore pressure in this depth interval in a way that the resulting intergranular effective stress has remained constant or decreased somewhat.

The electrical resistivity log (fig. 2) suggests that clay beds may be about 10 to 20 m thick. Clay and silt sequences as thick as 13 m were penetrated during drilling (Arthur Clark, U.S. Geological Survey, written commun., 1992). Measured hydraulic-conductivity values of clay samples from cores ranged from 1×10^{-6} to 4×10^{-3} m/day during laboratory consolidation testing at effective stresses equivalent to *in situ* burial depths (Harold Olsen, Colorado School of Mines, written commun., 1997). If these values are representative of *in situ* clay vertical hydraulic-conductivity values, the time required for clay pore-pressure equilibration may be calculated (Scott, 1963; Riley, 1969) assuming reasonable values of clay-unit specific storage. For a 13-m-thick clay bed with a vertical hydraulic conductivity of 1×10^{-6} m/day and specific storage of 3×10^{-4} m^{-1}, the time required to reach 93 percent of total consolidation is 32 years.

SUMMARY

Compaction of aquifer-system sediments between 6 and 340 m in depth resulted in land subsidence of 1.6 cm at the El Paso extensometer site for the period of record between April 2, 1993, and June 13, 2002. As much as 9 mm of compaction occurred in the deeper aquifer interval (100 to 340 m) before July 2000. This compaction likely was a response to ground-water withdrawals. As much as 7.6 mm of compaction has occurred in the shallow aquifer-system interval (6 to 100 m). Because individual clay unit thicknesses of about 10 m exist within the aquifer system at this location, the time required for pore pressures within low-permeability clays to equilibrate with those in the surrounding, more permeable sands may be tens of years. Residual compaction of several cm will likely continue because of this equilibration process, even if water levels measured in the permeable sandy parts of the aquifer system stabilize. Continued maintenance of the El Paso extensometers would document this process.

SELECTED REFERENCES

Galloway, D.L., Jones, D.R., and Ingebritsen, S.E., eds., 1999, Land subsidence in the United States: U.S. Geological Survey Circular 1182, 175 p.

Heywood, C.E., 1993, Monitoring aquifer compaction and land subsidence due to ground-water withdrawal in the El Paso, Texas - Juarez, Chihuahua, area, *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.

———1995, Investigation of aquifer-system compaction in the Hueco Basin, El Paso, Texas, USA, *in* Proceedings of the Fifth International Symposium on Land Subsidence, The Hague: International Association of Hydrological Sciences Publication 234, IAHS Press, Oxfordshire, UK, p. 35-45.

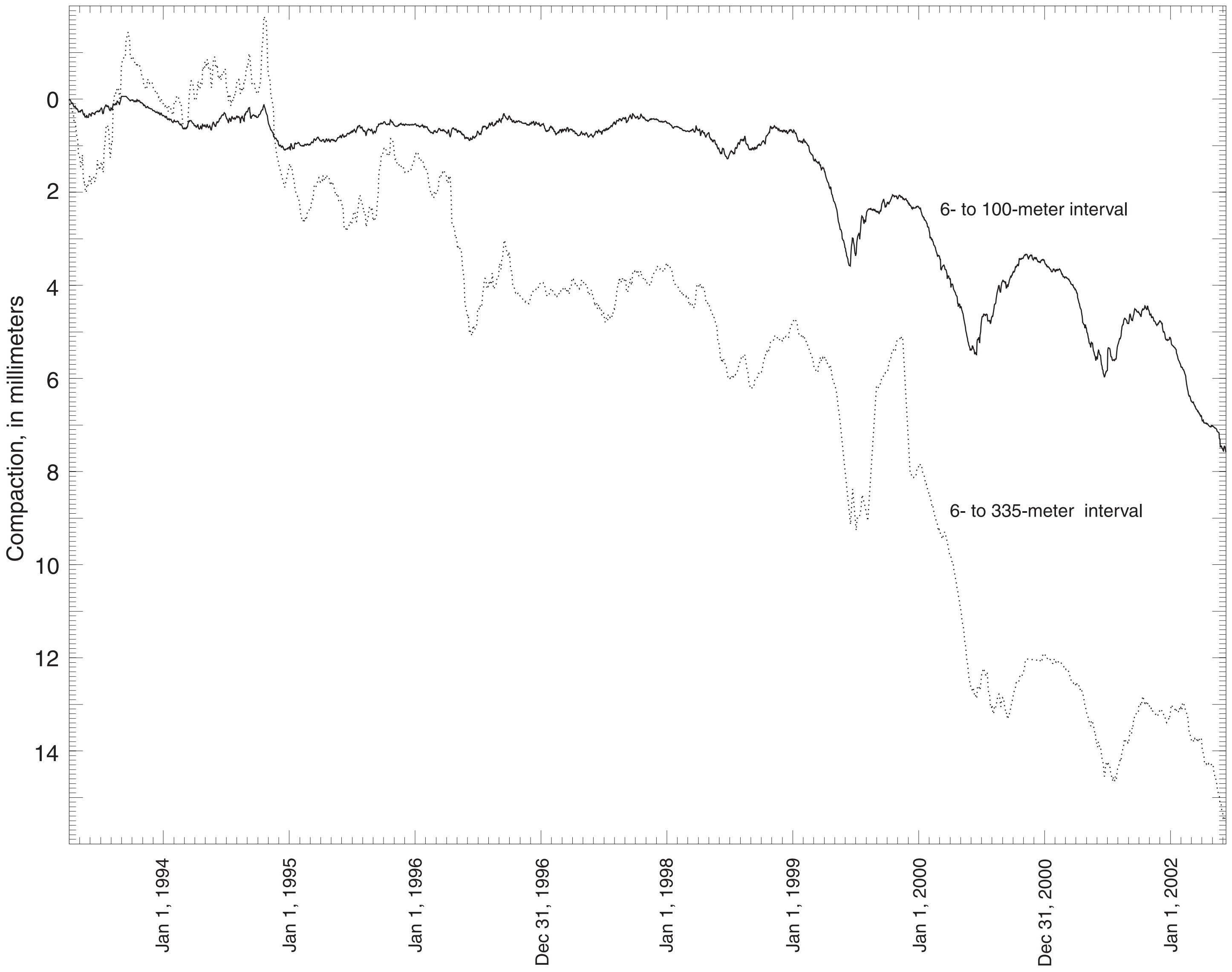

Figure 5. El Paso extensometer displacements.

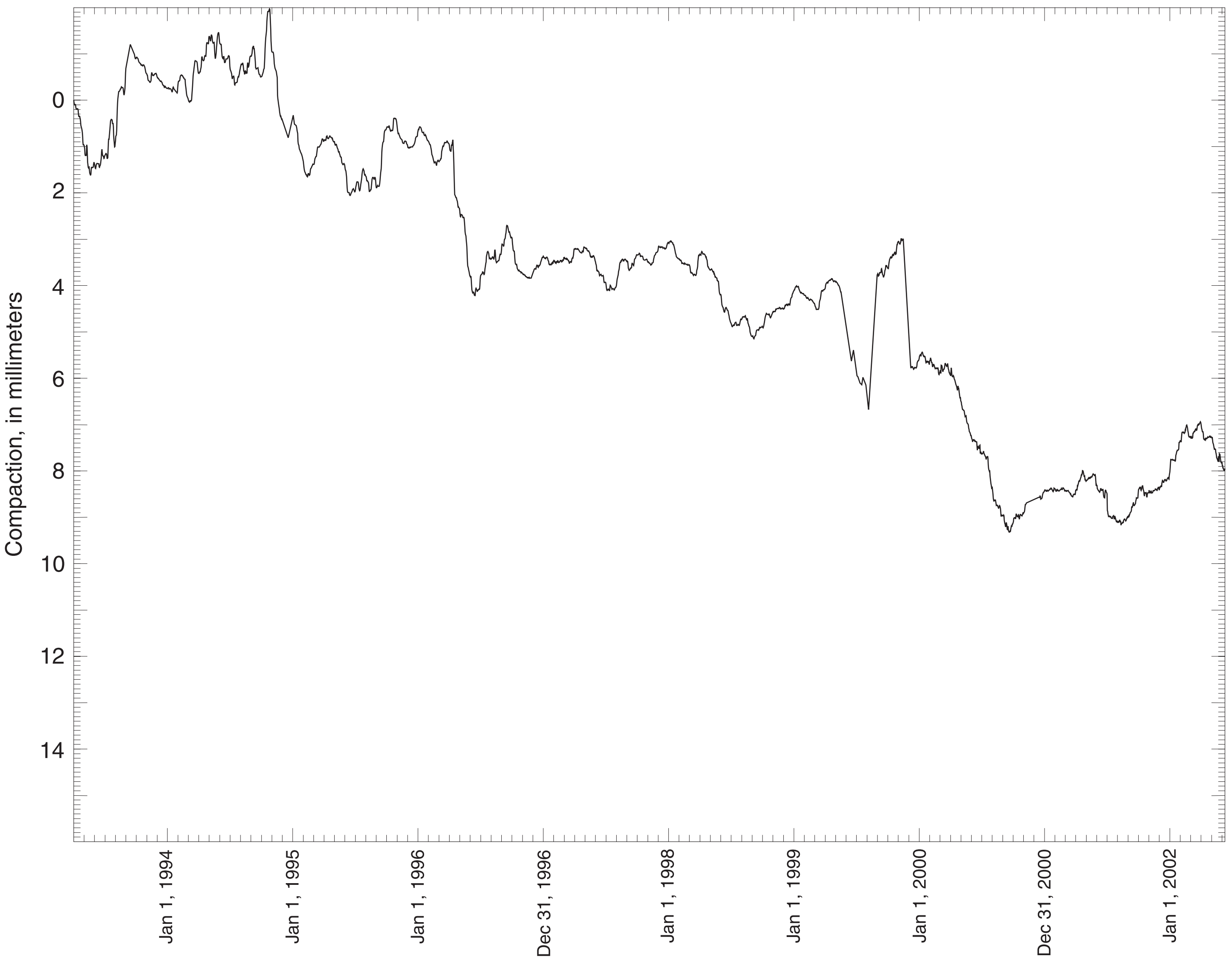

Figure 6. Measured compaction in the depth interval from 100 to 335 meters.

Heywood, C.E., 2000, Extensometers as seismometers: American Geophysical Union Transactions, v. 81, no. 48, abstract S11B-16.

Heywood, C.E., and Yager, R.M., 2003, Simulated groundwater flow in the Hueco Bolson, an alluvial-basin aquifer system near El Paso, Texas: U.S. Geological Survey Water-Resources Investigations Report 02-4108, 73 p.

Land, L.F., and Armstrong, C.A., 1985, A preliminary assessment of land-surface subsidence in the El Paso area, Texas: U.S. Geological Survey Water-Resources Investigations Report 85-4155, 96 p.

Riley, F.S., 1969, Analysis of borehole extensometer data from central California, *in* Tison, L.J., ed., Land subsidence: Proceedings of the International Symposium on Land Subsidence, Tokyo, International Association of Scientific Hydrology Publication no. 89, p. 423-431.

———1986, Developments in borehole extensometry, *in* Johnson, A.I., Carbognin, L., and Ubertini, L., eds., Land subsidence: Proceedings of the Third International Symposium on Land Subsidence, Venice, Italy, 1984, International Association of Scientific Hydrology Publication no. 151, p. 169-186.

Scott, R.F., 1963, Principles of soil mechanics: Palo Alto, Calif., Addison-Wesley Publishing Company, 550 p.