RESULTS OF SIMULATIONS BY A PRELIMINARY NUMERICAL MODEL OF LAND SUBSIDENCE IN THE EL PASO, TEXAS, AREA

By John Michael Kernodle

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 92-4037

Prepared in cooperation with the

UNITED STATES SECTION

INTERNATIONAL BOUNDARY AND WATER COMMISSION

UNITED STATES AND MEXICO

Albuquerque, New Mexico

1992

U.S. DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Water Resources Division
Pinetree Corporate Centre
4501 Indian School Rd. NE, Suite 200
Albuquerque, New Mexico 87110

Copies of this report can be
purchased from:

U.S. Geological Survey
Books and Open-File Reports
Federal Center
Box 25425
Denver, Colorado 80225

CONTENTS

FIGURES

FIGURES--Concluded

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (per year)	1,233	cubic meter (per year)
cubic foot per second	28.32	liter per second
foot (per second, per day, per year)	0.3048	meter (per second, per day, per year)
per foot	3.281	per meter
gallon	3.785	liter
gallon	0.003785	cubic meter
gallon per minute	0.06309	liter per second
million gallons per day	0.04381	cubic meter per second
million gallons per day	3,785	cubic meter per day
mile (per hour)	1.609	kilometer (per hour)
square mile	2.590	square kilometer

Sea level: In this report, sea level refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

RESULTS OF SIMULATIONS BY A PRELIMINARY NUMERICAL MODEL OF LAND SUBSIDENCE IN THE EL PASO, TEXAS, AREA

by John Michael Kernodle

ABSTRACT

A computer program module to simulate interbed compaction and land subsidence was added to an existing finite-difference ground-water-flow model developed for the City of El Paso, Texas. The combined subsidence and flow model was then calibrated to measured subsidence in the El Paso, Texas, area for the period 1954-84. Care was taken not to alter the mass balance of the existing calibrated ground-water-flow model.

The calibrated subsidence model used simulated coefficients of storage and calculated rates of land subsidence per unit head decline that are consistent with elastic deformation of the Hueco Bolson and shallow alluvial aquifers. The specific storage of the aquifer was simulated to be 2.0×10^{-5} per foot and the volume of compressible material was assumed to be 20 percent of the aquifer. The simulated ratio of land subsidence to unit change in head was 4.2×10^{-3} for the period 1992-2010.

The subsidence model was used to explore the possible effects on ground-water levels and land subsidence for a proposed diversion of water from an approximate 13-mile reach of the Rio Grande into a network of canals. The purposes of the proposed diversion are to allow more efficient water delivery to agricultural users, and to reduce losses to direct evaporation, riverbed seepage (channel loss), and unauthorized diversions.

Estimates of future land subsidence were made using the projected ground-water withdrawals of the model prepared for the City of El Paso for the period 1992 to 2010. The simulations of subsidence were performed for two scenarios: with diversion and without diversion of flow from the Rio Grande along a 13-mile reach of channel. The resulting changes in riverbed seepage, water-level altitude, and land subsidence were compared for the two scenarios. The simulations indicated that the riverbed seepage would decline from its predicted maximum of 35,200 acre-feet per year by 1992 to about 14,000 acre-feet per year should the diversion take place as proposed. Water-level declines that might occur as a result of the proposed diversion would increase 50 feet or less by 2010. Finally, land subsidence that without the proposed diversion would be slightly more than 1 foot in some areas by 2010 would increase by slightly less than 0.1 foot (generally, 0.06 foot or less) should diversion of flow take place.

INTRODUCTION

A major portion of the metropolitan El Paso, Texas/Ciudad Juarez, Mexico, area has been affected by as much as 0.41 foot of land subsidence between the mid-1950's and the mid-1980's (Land and Armstrong, 1985). The subsidence is regional in extent, as shown later in this report, but locally is significantly differential, causing some minor damage to residential structures (Land and Armstrong, 1985, p. 51). The immediate cause of past and current subsidence is continued declines in potentiometric heads in the Hueco Bolson and shallow alluvial aquifers. These declines are caused by ground-water withdrawals that exceed natural and induced ground-water recharge. The declines in potentiometric head cause the structural matrix of compressible interbed clays within the aquifers to loose hydrostatic support and collapse, initially causing recoverable compaction but eventually causing irreversible compaction.

The United States Section of the International Boundary and Water Commission has a proposal before the United States Congress to divert surface water owned by the United States from an approximate 13-mile reach of unlined channel of the Rio Grande into a network of existing and proposed canals to more efficiently deliver water to agricultural users, reduce losses to direct evaporation and riverbed seepage (channel loss), and prevent unauthorized diversions. Major concerns regarding the planned diversion are the direct and indirect effects that it might have on the existing rate and eventual magnitude of land subsidence.

Purpose and Scope

This report describes a numerical evaluation of the potential for additional subsidence in the El Paso, Texas, and Ciudad Juarez, Chihuahua, Mexico area as a result of the proposed diversion of water from an approximate 13-mile reach of the Rio Grande into a series of canals on the United States side of the Rio Grande channel. An existing finite-difference ground-water-flow model coupled with an interbed-compaction, elastic- and inelastic-storage computational package was used to simulate land subsidence that might result from declines in ground-water potentiometric heads. Because of the urgent need for this preliminary numerical evaluation, an existing calibrated ground-water-flow model provided by the City of El Paso was used. The scope of this report is limited to presenting the results of the land-subsidence simulations.

Previous Investigations

Two earlier reports--Land and Armstrong (1985) and Lee Wilson and Associates (1985b)--were the primary references for subsidence and flow modeling for this study. The report by Land and Armstrong (1985) provides a quantitative description of the factors affecting land subsidence in the Hueco Bolson (fig. 1) and also documents measured historical subsidence. The report by Lee Wilson and Associates (1985b), prepared for the City of El Paso, documents the calibrated transient ground-water-flow model that was used as the basis for the additional subsidence reconstructions and projections that were developed for this study.

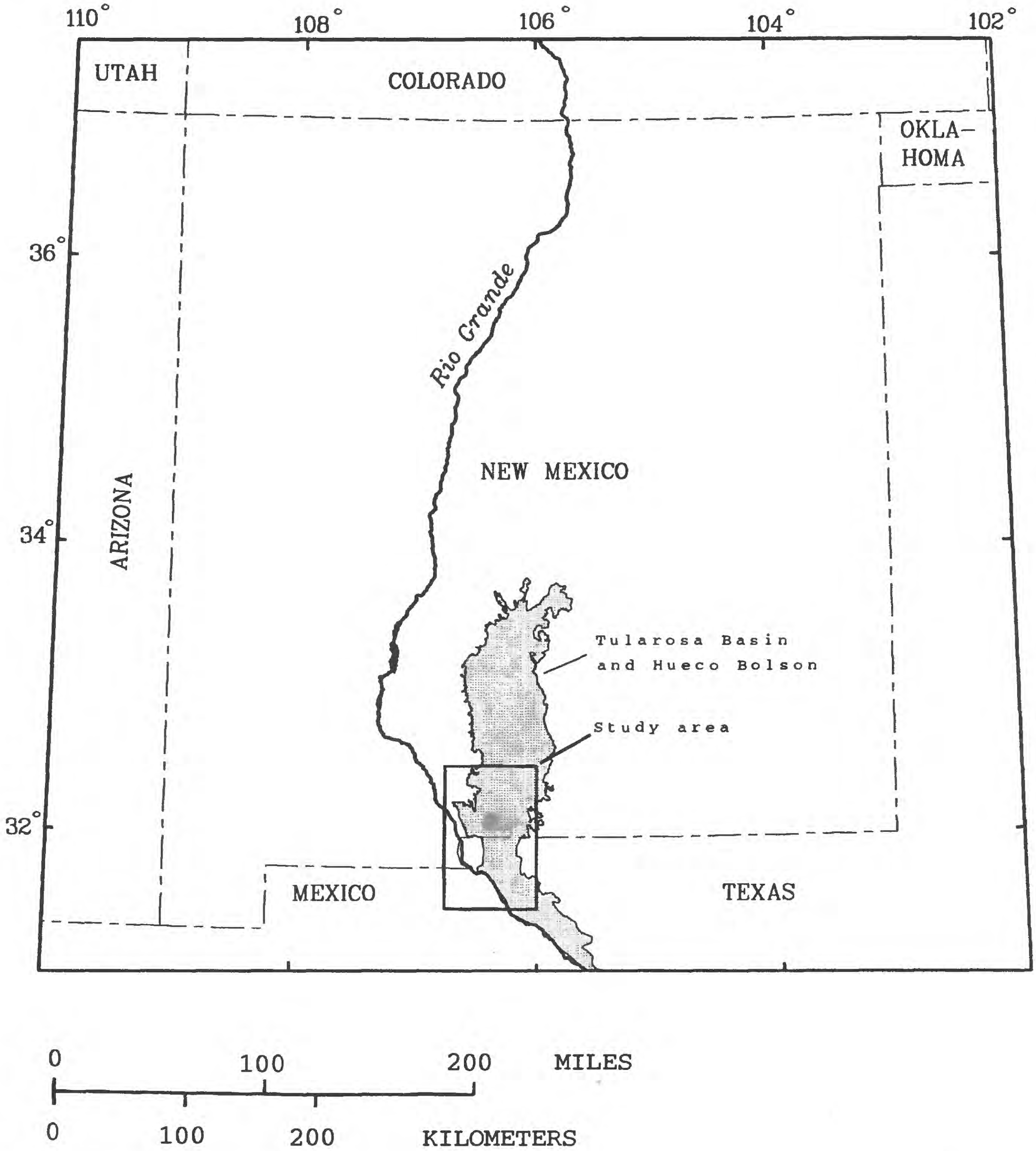

Figure 1.--Location of the study area.

Other ground-water-flow models of the Hueco Bolson and the northwardly contiguous Tularosa Basin have been constructed. The first of these was an electric-analog model (Leggat and Davis, 1966). Later, a semi-three-dimensional digital model was prepared by Meyer (1976), and was then revised and updated by Knowles and Alvarez (1979). To the north, in the Tularosa Basin, models have been prepared by Kelly and Hearne (1976), Burns and Hart (1988), Risser (1988), and most recently by Orr and Risser (in press). Some of these models overlap parts of the Hueco Bolson. A review and summary of the models completed prior to 1985 may be found in a report by Kernodle (1992).

Several references describe the generalized geohydrologic setting in the Hueco Bolson. Knowles and Kennedy (1958) were among the first to describe in detail the ground-water resources of the area. Davis (1967) and Davis and Leggat (1967) documented the water chemistry and quality of the ground water in the bolson. Other works have been prepared concerning the geohydrology of the area but those by White (1983) and Lee Wilson and Associates (1985a) are among the most recent and comprehensive.

One of the more frequently cited articles on the subject of subsidence is by Holzer (1981) in which he discusses preconsolidation stress in aquifer systems. The previously mentioned report by Land and Armstrong (1985) is the first and possibly only formal documentation of land subsidence in the El Paso, Texas/Ciudad Juarez, Mexico area. However, Laney (1976) documented subsidence in a similar geohydrologic setting in south-central Arizona where efforts continue to document and research the problem. A report by Leake and Prudic (1988) documents the computer program used in this report to calculate land subsidence based on changes in potentiometric head. The subsidence computer program is a module added to the finite-difference ground-water-flow model documented by McDonald and Harbaugh (1988). Other articles by Leake (1990, 1991) discuss the theory and application of numerical modeling of land subsidence.

GEOHYDROLOGY OF THE TULAROSA BASIN AND HUECO BOLSON

The Tularosa Basin and Hueco Bolson together comprise one of the 22 geologic structural rift basins defined in the eastern part of the Southwestern Alluvial Basins regional geohydrologic province (Kernodle, 1992). The Tularosa-Hueco rift basin is approximately 200 miles long in a north-south direction and 40 miles wide at its widest point (fig. 1). The southern part of the rift basin is known as the Hueco Bolson and within that area is the legally defined Hueco (ground-water) Basin. The only physical evidence of a separation of the Tularosa Basin from the Hueco Bolson is a very minor topographic divide near the New Mexico-Texas State line.

Typical of the rift basins, the north and south limits of the Tularosa-Hueco Basin are determined by the convergence of structural features. Atypically, however, the southwest structural limit of the basin is defined by a subtle but geologically significant northwest-trending geologic feature known as the Texas Lineament, which separates Laramide Basin and Range geologic features from those of the Rio Grande rift. The eastern and western limits are defined by surface outcrops of pre-Tertiary geologic units.

On the eastern flank of the Franklin and Organ Mountains (fig. 2) faulting has lowered the basin floor and elevated the adjacent mountain block. Davis and Leggat (1967) estimated the displacement to be more than 9,000 feet. Lovejoy and Hawley (1978) credited other workers who estimated that the differential displacement may be as much as 30,000 feet. Lovejoy and Hawley (1978, p. 57) also estimated that the basin-fill sediments in this area may be as much as 5,000 feet thick. On the eastern side of the basin, however, faults are either absent or much more subtle, and the pre-Tertiary sediments appear to gradually rise to the land surface.

The basin-fill deposits (fig. 2) are composed of lacustrine clays and silts, fluvial sands and gravels, eolian sands, and fanglomerates. Basalt flows, caliche, anhydrite, and gypsum also are present at or near land surface. The Santa Fe Group of Tertiary and Quaternary age is the principal water-yielding unit in the Hueco Bolson. The Santa Fe Group consists of two units: the lower Fort Hancock Formation and the overlying Camp Rice Formation. The Fort Hancock Formation generally is identified as lacustrine and playa sediments predominantly consisting of interbedded clays and silts, especially in the central and eastern parts of the structural basin. Along the western basin margin, intertonguing alluvial-fan deposits are common in the Fort Hancock Formation. The Camp Rice Formation generally is of fluvial origin from the ancestral Rio Grande, which is thought to have once flowed through Fillmore Pass between the Organ and Franklin Mountains. The Camp Rice Formation consists of sands and gravel with some interbedded clays. The Santa Fe Group is overlain by basalt flows, a veneer of eolian sand in the bolson area, alluvial-fan deposits along the basin margin, and by incised Rio Grande alluvium of Holocene age in the inner valley of the Rio Grande.

The primary occurrence of fresh ground water in the Hueco Bolson is in an irregularly shaped wedge of water bordering the Franklin and Organ Mountains (fig. 2). This wedge of freshwater overlies saline water (generally coincident with the Fort Hancock Formation) and is kept fresh by mountain-front recharge. Sayre and Livingston (1945) estimated the amount of recharge to be 13 million gallons per day (about 14,600 acre-feet per year). The area of freshwater extends southward beyond the Franklin Mountains into what is commonly called the artesian area beneath El Paso and Ciudad Juarez, but is bounded on the top, bottom, and east side by saline water. The area outside the inner valley of the Rio Grande (also called the lower El Paso Valley) is often called the mesa, the bolson area, or the water-table area.

The shallow alluvial aquifer in the incised Rio Grande valley is about 200 feet thick, placing the base of the aquifer about 400 feet below the land surface of the adjacent bolson area. The alluvium is in good hydraulic connection with the older basin-fill deposits and with the graded but unlined portions of the Rio Grande channel. Land and Armstrong (1985) estimated that ground-water withdrawals have induced recharge of about 30,000 acre-feet per year from unlined sections of the Rio Grande. Hydraulic connection between canals in the inner valley and the alluvial aquifer is significantly poorer than between the river and the alluvium because of canal lining and other engineering practices.

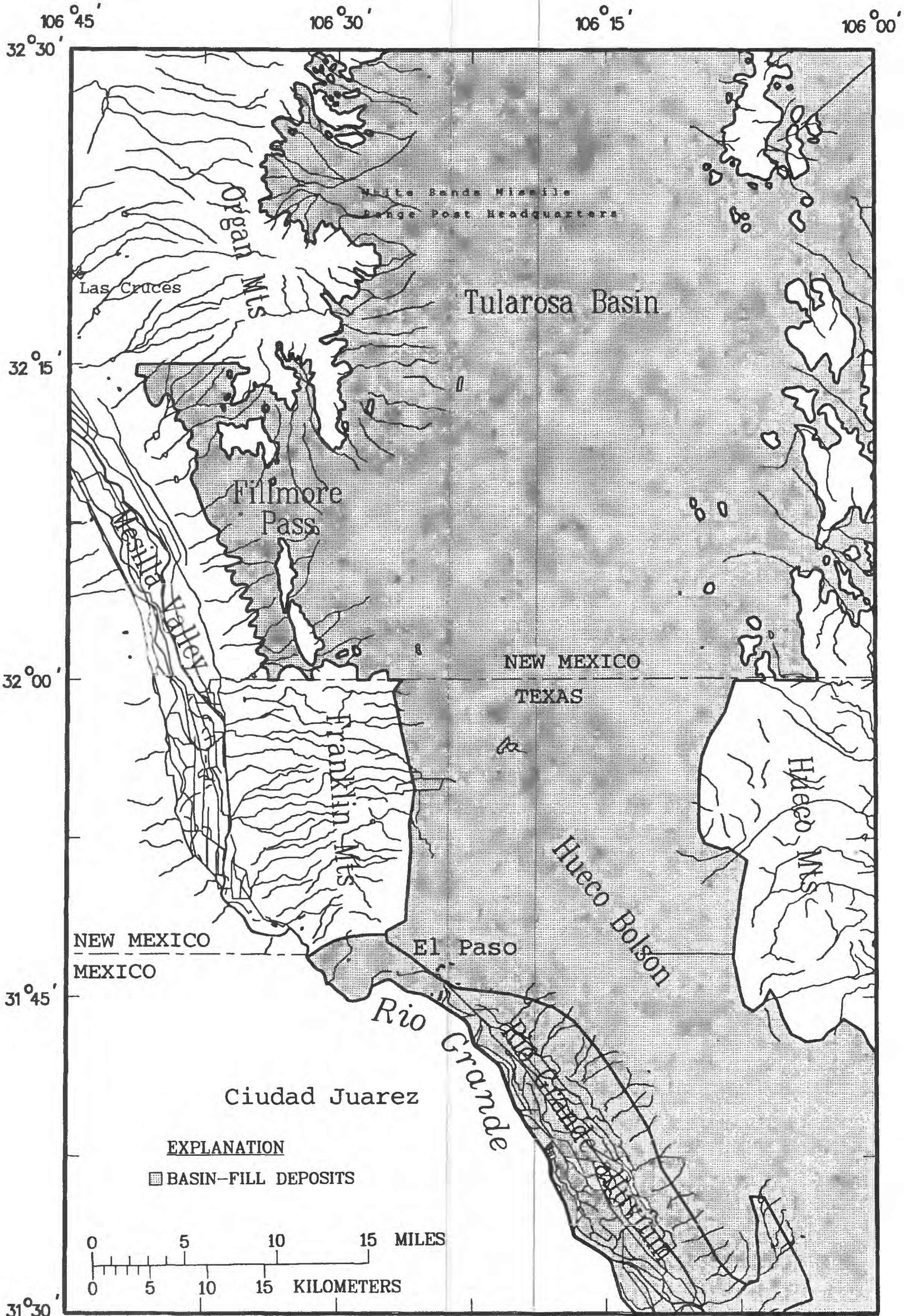

Figure 2.--Area of basin-fill deposits and selected features in the study area.

LAND SUBSIDENCE

Land subsidence results from compaction of earth material under conditions of increased stress or some form of alteration of the mechanical structure of earth materials. According to a recent international survey on land subsidence by the International Association of Hydrological Sciences, the results of which have not yet been published, land subsidence may result from a single cause or a combination of causes: fluid withdrawal from a geologic unit, application of water (hydrocompaction), dewatering of organic soils, loading by engineering structures, mining, solution of subsurface materials of which karst collapse is a component, geologic loading, and tectonic or volcanic activity. This study addresses only the interbed compaction and resulting land subsidence that is caused by removal of water from the aquifers in the El Paso, Texas, area.

Ground-water withdrawal causes a decline in ground-water levels (potentiometric head), which can result in interbed compaction and land subsidence. For years hydrologists and soil scientists (Theis, 1935; Terzaghi, 1936; Terzaghi and Peck, 1948) have recognized the importance of elastic and inelastic yield of water from aquifers and soils. Theis' 1935 work was the first to demonstrate that aquifer storage may account for all of the volume of water discharged from a well completed in an artesian aquifer. He did not, however, consider the physical changes that occur in the aquifer as a result of the change in internal hydrostatic pressures caused by removal of water from storage. Terzaghi (1936), however, was concerned with the effects of the change in hydrostatic stress from "neutral" to "effective" and the resulting changes in soil behavior (for example, compressibility). It was not until the early and mid-1960's, when land subsidence resulting from ground-water depletion became a serious problem in parts of the United States, that the pace of research in the field increased.

According to Domenico and Mifflin (1965, p. 1), "Seepage pressures are part of the neutral or nondeformative stresses acting in a groundwater basin. The reduction of these pressures gives rise to a stress transfer from neutral to effective. The increase in effective stresses is exclusively responsible for measurable deformations of the land surface. The amount of land subsidence or groundwater recovery from compressible confining layers depends on the specific storage of the strata and the average head change within them." In their analysis of the specific storage of confining layers, pore-water-pressure decay, and land subsidence, they presented a table of bulk modulus of compression and specific storage of various typical aquifer-system lithologies ranging from plastic clay to sound rock. Their reported range of specific storage for typical unconsolidated sediments was from 6.2×10^{-3} per foot for plastic clay to 1.5×10^{-5} per foot for dense sandy gravel (Domenico and Mifflin, 1965, table 1).

In water-table aquifers such as the Hueco Bolson, where perhaps 20 percent of the volume of aquifer material dewatered is water produced by the draining of aquifer porosity, the observation of the mechanics and effects of compaction is obscured and delayed: withdrawal of a large volume of water results in only a minor change in hydrostatic physical stress and resultant strain on the aquifer matrix. Thus a very large amount of water must be withdrawn to produce a water-level decline sufficient to produce significant compaction. However, in a water-table aquifer there are two components of the mechanism of subsidence due to removal of water from the aquifer system. One is the compaction that results from lowering of hydrostatic pressure supporting the saturated solid matrix. The second component, not considered in this study, is the compaction that results from the eventual complete desaturation under inelastic conditions of fine-grained, water-bearing sediments left stranded above a declining water table.

As discussed in Domenico and Mifflin (1965) and Leake and Prudic (1988) land subsidence results from the compaction of interbed clay lenses within the aquifer. Land and Armstrong (1985) estimated the combined thickness of clay lenses in the freshwater zone in the Hueco Bolson to be from 50 to 450 feet. However, saturated clay lenses above and below the freshwater zone are also affected by changes in hydrostatic pressure. Therefore, the total thickness of clay that is subject to compaction may be greater than Land and Armstrong's (1985) estimate.

Compaction is a result of elastic and inelastic deformation. As the effective stress on the aquifer system increases, elastic deformation occurs up to the point where a previous maximum stress is reached. At and beyond this stress, known as the preconsolidation stress, most of the deformation is inelastic and unrecoverable. Also at this stress, changes take place in the yield of water and rate of subsidence per unit change in head in the aquifer. The specific storage resulting from inelastic deformation may be as much as two orders of magnitude greater than that of elastic deformation, and the rate of land subsidence per unit decline in head may increase tenfold. The following table from Land and Armstrong (1985) is a summary of the water-level declines needed to reach preconsolidation stress, and rates of land subsidence before and after the preconsolidation stress was reached (table 1).

GROUND-WATER-FLOW MODEL

The three-dimensional ground-water-flow model used in this study as the basis for the subsidence simulations was developed for the City of El Paso and is documented in a report by Lee Wilson and Associates (1985b). The flow model was used to explore alternatives for ground-water development including scenarios of development along the western side of the basin in the southern part of the Tularosa Basin and northern part of the Hueco Bolson. This model was chosen over the others cited earlier because it most fully represented the three-dimensional nature of the ground-water flow system, was the most current, and the model input data were compatible with the Survey's modular ground-water-flow model (McDonald and Harbaugh, 1988); hence, the subsidence module (Leake and Prudic, 1988) that was used for this study could readily be adapted. This report is not intended to redocument the calibration of the ground-water-flow model. The validity of the results of this study depend on the accuracy with which the model predicts changes in head in the system.

Table 1.--Land subsidence per unit water-level decline

[Modified from Land and Armstrong, 1985, table 5; and from Holzer, 1981, table 1]

Reference point	Land subsidence per unit water-level decline for declines less than preconsolidation stress	Land subsidence per unit water-level decline for declines greater than preconsolidation stress	Water-level decline at preconsolidation stress (feet)
	Eloy-Picacho area, Arizona		
A279	<0.00538	0.0373	92
RV329	.00175	.0392	>69
RV330	.00091	.0426	115
D279	.00304	.0531	109
	Houston-Galveston area, Texas		
V8	0.01033	0.0358	102*
R8	<.00844	.0320	125*
P54	.01073	.0322	175*
S54	.00947	.0355	207*
N8	.00719(?)	.0273(?)	184*
	Tulare-Wasco area, California		
341.804B	0.00250	0.0335	85*
292.116B	<.01197	.0463	<85*
	Santa Clara Valley, California		
P7	0.00849(?)	0.1245(?)	<52(?)*

*Based on depth to water from land surface
< Less than
> Greater than
? Questionable observation as reported by Holzer, 1981.

The model employs 41 rows, 18 columns, and 4 layers to simulate the freshwater ground-water flow in an area of about 1,700 square miles. Figure 3 shows the location of the area simulated and the configuration of the finite-difference model grid. The cell dimensions range from 1 to 4 miles and are smallest in the vicinity of El Paso, Texas, and along the eastern flank of the Franklin Mountains--areas where the highest simulation accuracy was sought. The depth simulated was to the base of freshwater, which ranged from zero to about 1,400 feet. The top layer was simulated as being unconfined and the remaining three layers were simulated as being confined but with the option to convert to unconfined should the potentiometric head decline below the top of the cell.

A steady-state model simulation was run to precondition the starting potentiometric heads for the transient simulations. The transient simulations of historical conditions began in 1880 and concluded in 1983. A partial year of withdrawal data was available for 1984. The model was run in two stages, 1880-1963 and 1964-83, for the transient calibration. The simulation of historical time to 1984 was divided into 14 stress periods. Transient calibration was based on areal potentiometric-head distributions at specific times (water-level contour maps) and on time-series changes in potentiometric head at specific locations (hydrographs). The mass balance of sources and sinks of water was also a calibration criterion.

The boundary conditions that were simulated included recharge along the Franklin and Organ Mountains (specified flux), evapotranspiration (a maximum rate of about 5 feet per year linearly decreasing to zero at an extinction depth of 15 feet), discharge to drains (a one-way general-head boundary), river interaction (a bidirectional general-head boundary with a limit on the maximum channel loss), and discharge from wells (specified flux). The simulation also included a few specified-head cells in the eastern part of the southern edge of the model. Discharge rates from wells and well locations were adjusted for each simulated stress period, and a portion of the cells representing the Rio Grande were removed from the simulation after 1967 (fig. 3). The removal of the river cells was intended to simulate the alignment and paving of a reach of the river known as the Chamizal.

The calibrated flow model was used to simulate various future scenarios regarding the location and rates of discharge from wells. The latest date reported for the projections of the flow model was 2010. Not included in the simulations were the recharge injections associated with a pilot study and the continued operation of a wastewater-recovery facility in northeast El Paso (White and Sladek, 1990): from 1985 through 1989 an average of 3.48 million gallons per day of treated wastewater was injected into the aquifer system. The scenario used in this study is the same as that used as the benchmark simulation for all the other scenarios prepared for the City of El Paso: projected increase in ground-water withdrawal with little areal expansion of existing well fields.

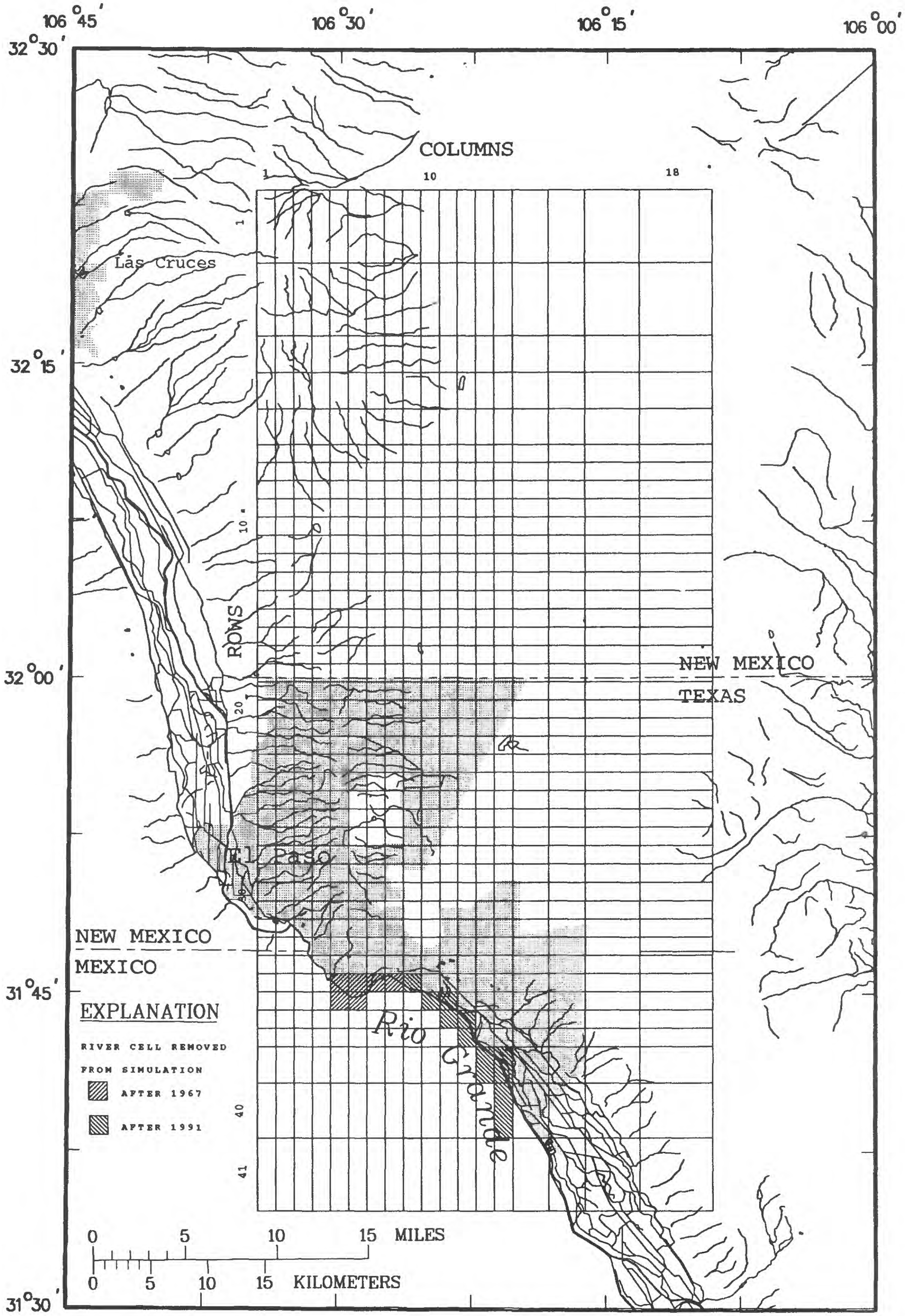

Figure 3.--Finite-difference grid and model cells representing the reach of the Rio Grande that might be affected by diversion of flow.

The unaltered model provided by Lee Wilson and Associates (1985b) was known to be somewhat unstable, especially near the end of the projected simulations. One of the causes was the complete isolation of a small block of cells from the remainder of the simulated aquifer system. Removal of this block of active cells resolved this problem without any impact on the simulation results of the documented model. Later in the simulations, as cells began to desaturate in response to simulated ground-water withdrawal, the potentiometric head of an occasional cell would gradually approach the altitude of the base of that cell. When this occurred, a minor change in head would result in a substantial change in transmissivity and the computed head would fall into a cycle of oscillations without converging on a solution. Because the cell seldom had as much as 0.5 foot of saturation when this happened, the selected corrective measure was to stop the simulation at this point and manually deactivate the cell.

Following the above procedure a simulation of the period 1880 to 2010 was made without any other changes to the model as it was originally prepared for the City of El Paso. This full-span simulation was used as the reference benchmark for the subsequent simulations that included interbed compaction and land subsidence. Land subsidence is computed by the model by summing the interbed compaction for all layers.

COUPLED GROUND-WATER-FLOW, LAND-SUBSIDENCE MODEL

When the additional source of water released from storage by elastic and inelastic interbed compaction was added to the model, the immediate concern was to guarantee that the resulting mass-balance calculations of the subsidence model did not differ from the calibrated benchmark model for at least the period of calibration. A significant change in the mass balance would indicate that the calibration of the flow component of the model was no longer valid. However, this was not a significant problem. The net difference in the storage component of the mass balance between the benchmark and subsidence models was less than 0.5 percent for the duration of the calibration period, even including the differences that arose from the manual deactivation of cells as mentioned above. To put this percentage in perspective, some of the benchmark simulation stages had overall mass-balance errors of nearly 0.1 percent due strictly to errors in numerical approximation.

Another concern is that no model is fully valid when performing analyses beyond its designed application. In this case, a model designed to explore the relative merits of a realm of possible future aquifer-development schemes was never intended to be used to replicate historical land subsidence. The proper approach under these circumstance is to proceed with the simulation effort but be constantly aware that problems may develop during the calibration attempt or that projections may be inaccurate.

Calibration

The subsidence module requires three arrays of information for each model layer. The information consists of the potentiometric head that is equivalent to the preconsolidation stress, the elastic storage coefficient, and the inelastic storage coefficient. Because the preconsolidation stress was unknown and because Land and Armstrong (1985) reported that the system did not appear to have exceeded the preconsolidation stress at the time of their investigation, the arrays of data were defined such that the model was forced to use exclusively the elastic storage coefficient. The calibration process described below could then be used to determine if and when this storage value needed to be increased into the inelastic range of values.

Compressible materials were first assumed to be uniformly distributed within the aquifer and the arrays defining the storage of these materials were defined as follows. First, the arrays were populated with the thickness of each layer as determined by subtracting the flow-model array defining the bottom of each cell from the array defining the top. Next, the compressible materials were assumed to occupy 20 percent of the volume of the aquifer. Finally, a specific-storage estimate for elastic storage was made for the compressible material. The latter two numbers (percentage of compressible material and elastic specific storage) were multiplied together and used as a multiplication factor against the arrays of layer thickness.

Early in the calibration process, the simulated subsidence systematically exceeded the reported amounts in a small area just south of the Franklin Mountains by as much as 0.2 foot for the period 1954 to 1984. According to Land (Larry Land, U.S. Geological Survey, oral commun., 1991), this area was an energetic reach of the Rio Grande as it first emerged from the Mesilla Basin and fine-grained compressible sediments may be less abundant here than as simulated. In the final model the simulated thickness of compressible materials in this area was reduced to one-half of the initial estimate.

The historical land-subsidence simulations were begun in the same year, 1880, as the benchmark ground-water-flow model and were run through 1983. The difference in subsidence between 1954 and 1984 was then calculated and compared with the reported subsidence for roughly the same time interval (Land and Armstrong, 1985, fig. 19 and table 6). This process was repeated with different estimates of the elastic specific storage until the reported and simulated subsidence were in close agreement (table 2). Figure 4 shows the simulated land subsidence from 1880 to 1954. Figure 5 shows the simulated subsidence from 1880 to 1984. Figure 6 shows the difference in subsidence between 1954 and 1984. Figure 7 shows the areal distribution of the difference between measured and simulated land subsidence. Data in table 2 and figure 7 may not agree, due to rounding. The specific storage that was used to obtain these results was 2×10^{-5} per foot, which is in agreement with the values reported by Land and Armstrong (1985).

Table 2.--Comparison between measured and simulated land subsidence for the period 1954 to 1984

[The value computed for the cell is the cell-centered average calculated by the model. The interpolated value was taken from spot samples on a continuous surface generated from the cell-centered values]

Model		Number of field measurements	Land subsidence, in feet (1954-84)		
Row	Column		Computed for cell	Mean field measurement	Mean interpolated from simulation
28	10	1	0.27	0.10	0.27
29	9	1	0.23	0.22	0.23
31	9	1	0.20	0.28	0.20
32	8	1	0.20	0.17	0.20
33	8	1	0.27	0.16	0.23
34	8	1	0.33	0.27	0.33
34	9	1	0.34	0.26	0.34
34	10	1	0.25	0.25	0.26
34	6	1	0.16	0.18	0.17
35	7	4	0.43	0.34	0.42
35	8	2	0.41	0.37	0.40
35	11	2	0.23	0.24	0.24
35	4	1	0.00	0.06	0.10
35	5	3	0.25	0.09	0.17
35	9	5	0.34	0.35	0.34
36	10	2	0.31	0.32	0.29
36	5	1	0.25	0.27	0.24
36	6	1	0.22	0.29	0.22
36	11	3	0.24	0.25	0.25
37	12	1	0.18	0.20	0.19
38	12	1	0.16	0.26	0.15
38	13	2	0.13	0.25	0.13
39	14	4	0.09	0.08	0.09
40	14	3	0.05	0.05	0.05
40	15	4	0.00	0.05	0.03

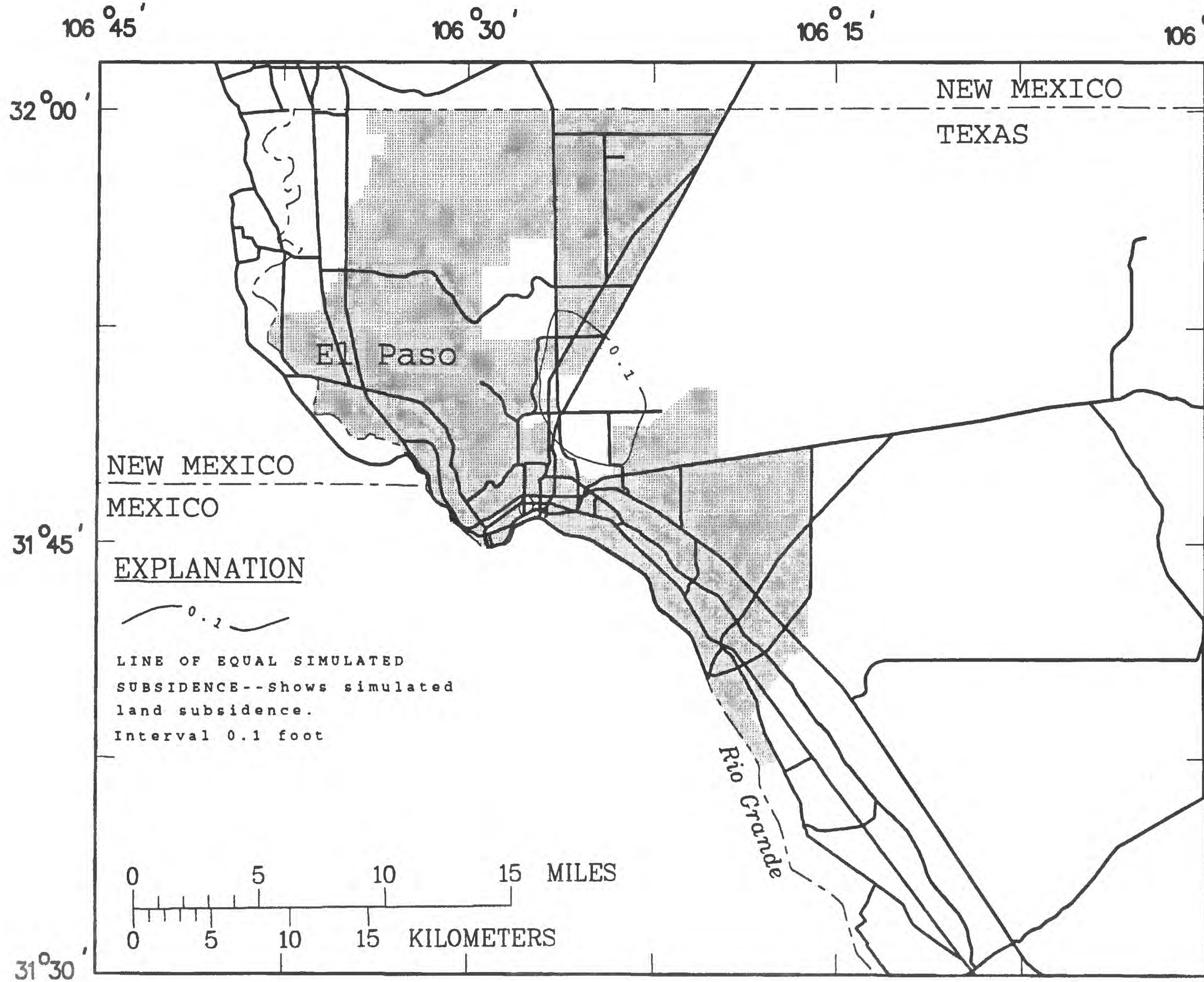

Figure 4.--Total simulated land subsidence from 1880 to 1954.

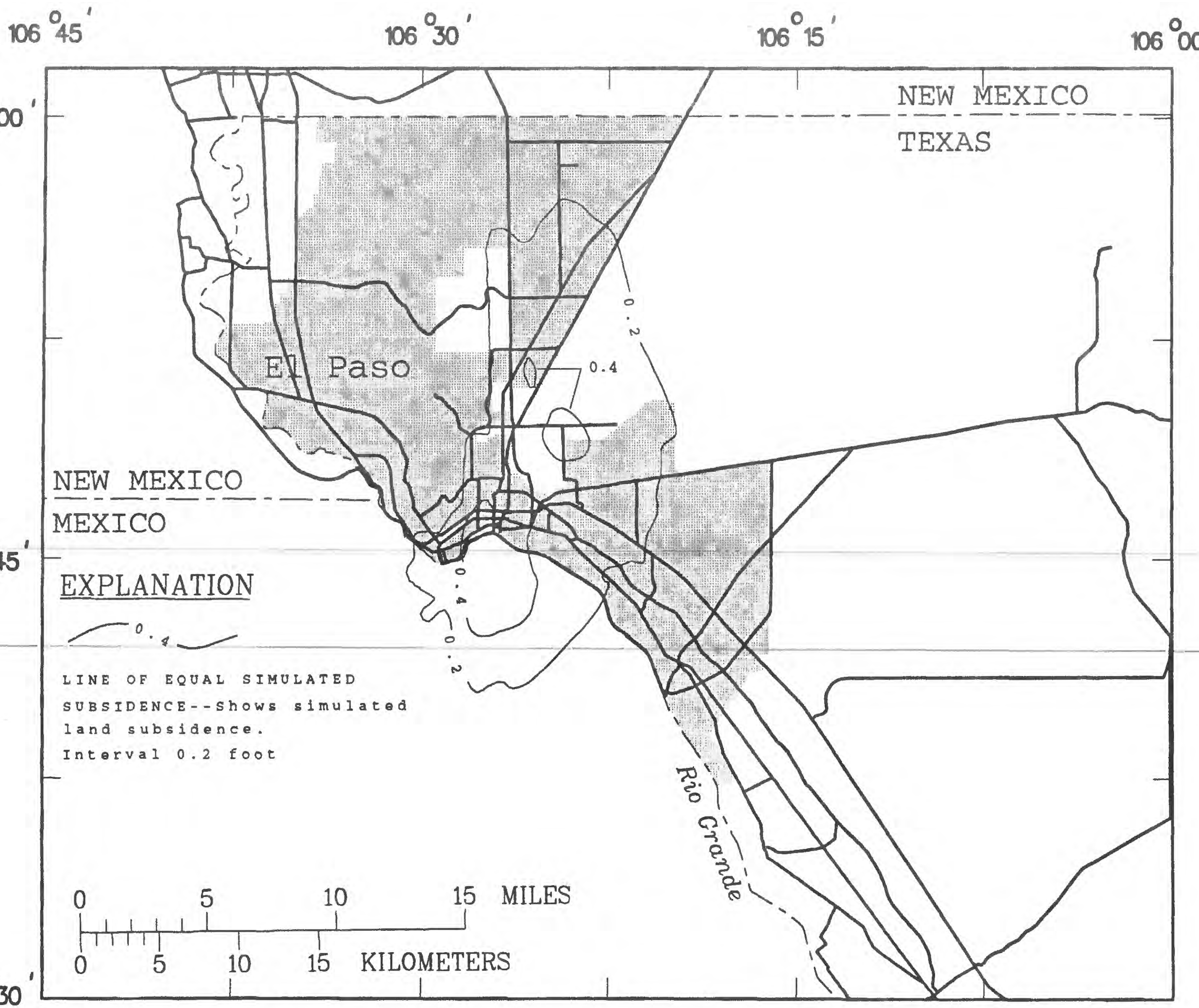

Figure 5.--Total simulated land subsidence from 1880 to 1984.

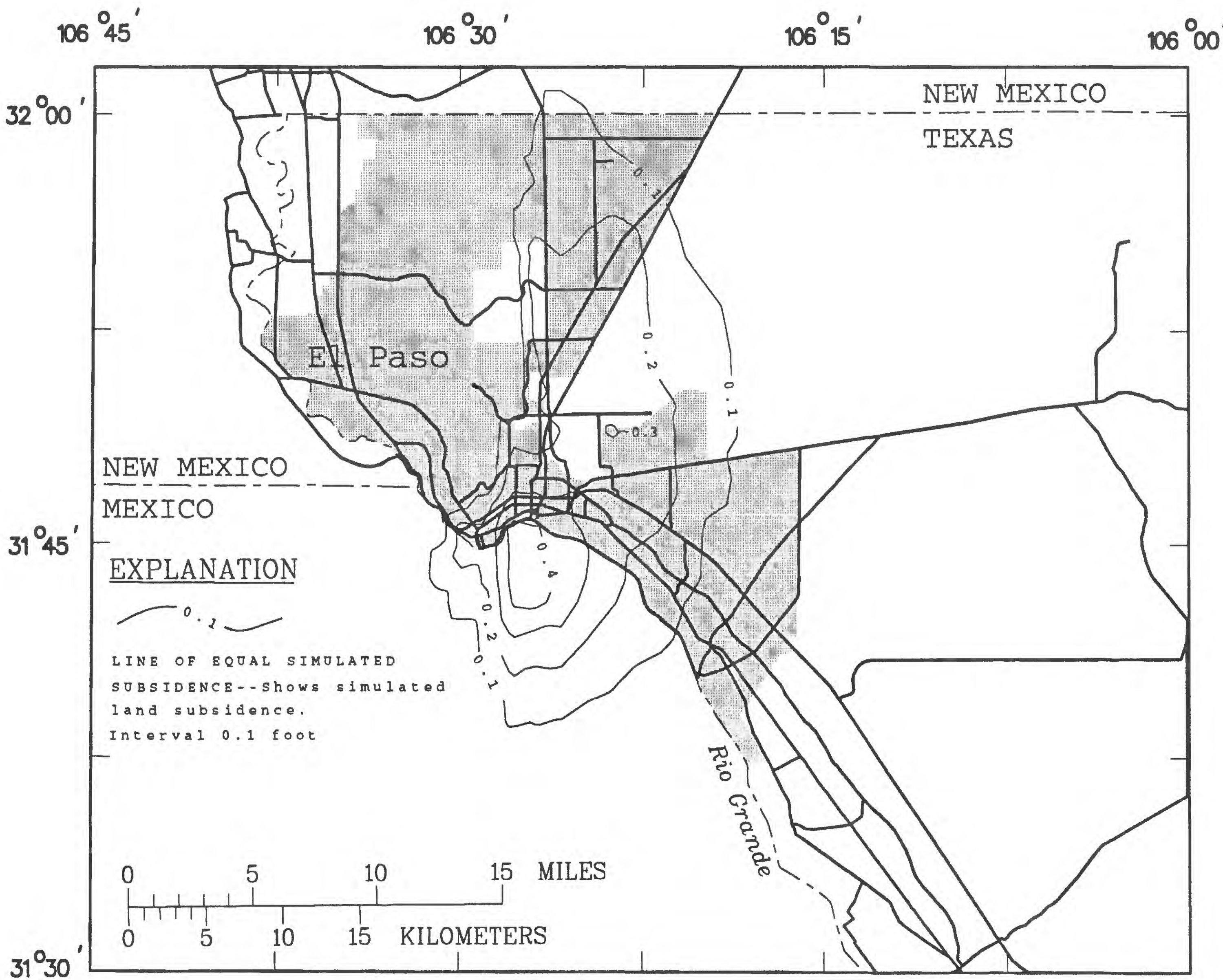

Figure 6.--Simulated net increase in land subsidence between 1954 and 1984.

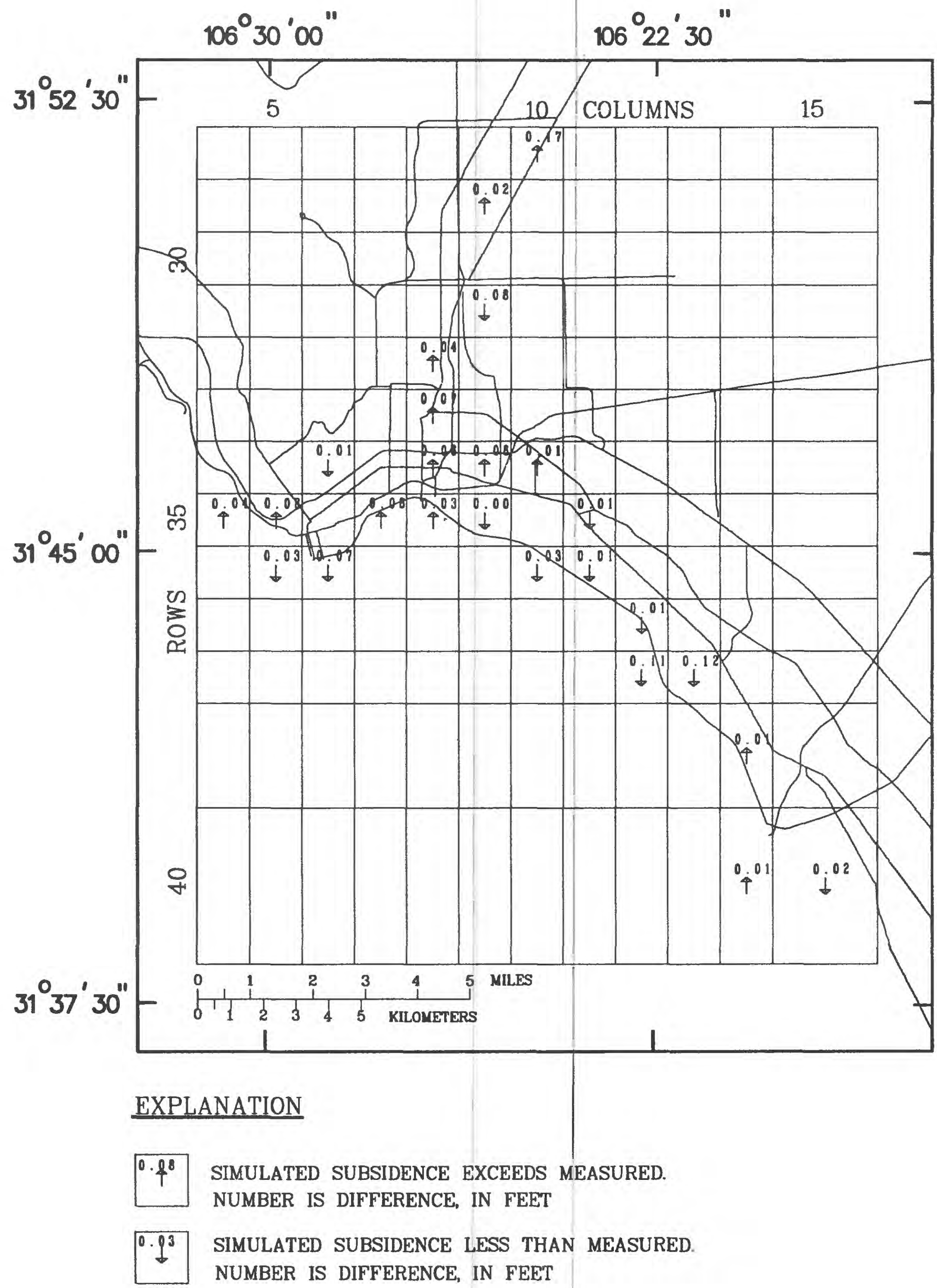

Figure 7.--Areal distribution of differences between measured and simulated land subsidence.

Projections

After the subsidence component of the model was calibrated, the model was used to project additional subsidence to 1992, 2000, and 2010. The simulated withdrawals from wells were the same as those in the benchmark flow model. The year 1992 was selected as the year in which water would be simulated as being diverted from the Rio Grande and into a series of new and existing canals and waterways, leaving an approximate 13-mile reach of the Rio Grande channel essentially dry much of the time, and greatly decreasing recharge to the aquifer. In actuality, some flow would occur in the Rio Grande as a result of storm runoff and agricultural return flow of excess irrigation water, but these intermittent flows were not simulated. Figure 3 shows the cells in the finite-difference model grid from which the simulated river boundary would be removed. To verify or update these simulations, 1992 was also selected with the hope that additional field data on land subsidence might be collected by that time. Figure 8 shows the projected total subsidence to 1992 and figure 9 shows the increase in land subsidence between 1984 and 1992.

Two sets of simulations were run for 1992-2010: one set simulated future land subsidence with unaltered flow in the Rio Grande and the other set simulated subsidence with flow diverted from the Rio Grande and into canals and lined waterways. Figures 10 and 11 show the projected total subsidence to 2000 with and without the proposed diversion. Figure 12 shows the simulated net increase in subsidence by 2000 that might occur as a result of the proposed diversion. Likewise, figures 13 and 14 show the projected total land subsidence to 2010 with and without the proposed diversion, and figure 15 shows the simulated net increase in land subsidence by 2010 that might occur as a result of the proposed diversion.

The coupled flow and subsidence model also calculated potentiometric head. Figures 16 and 17 show the water-table altitude of simulated head in the uppermost saturated model cell (several dozen model cells desaturated during the simulations) for 2010 with and without the proposed diversion. Figure 18 shows the simulated net decline in water level in 2010 that might occur as a result of the proposed diversion.

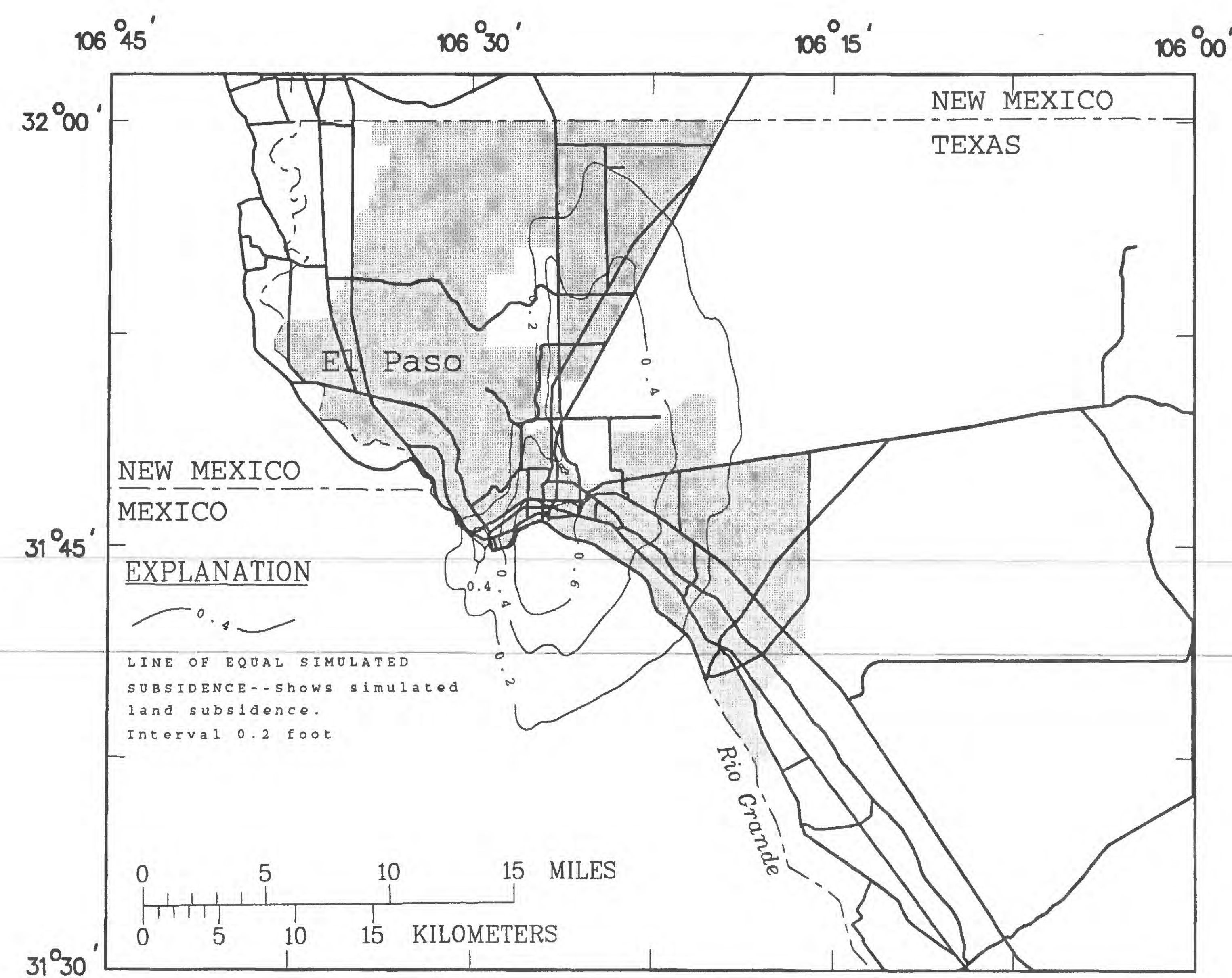

Figure 8.--Projected total land subsidence from 1880 to 1992.

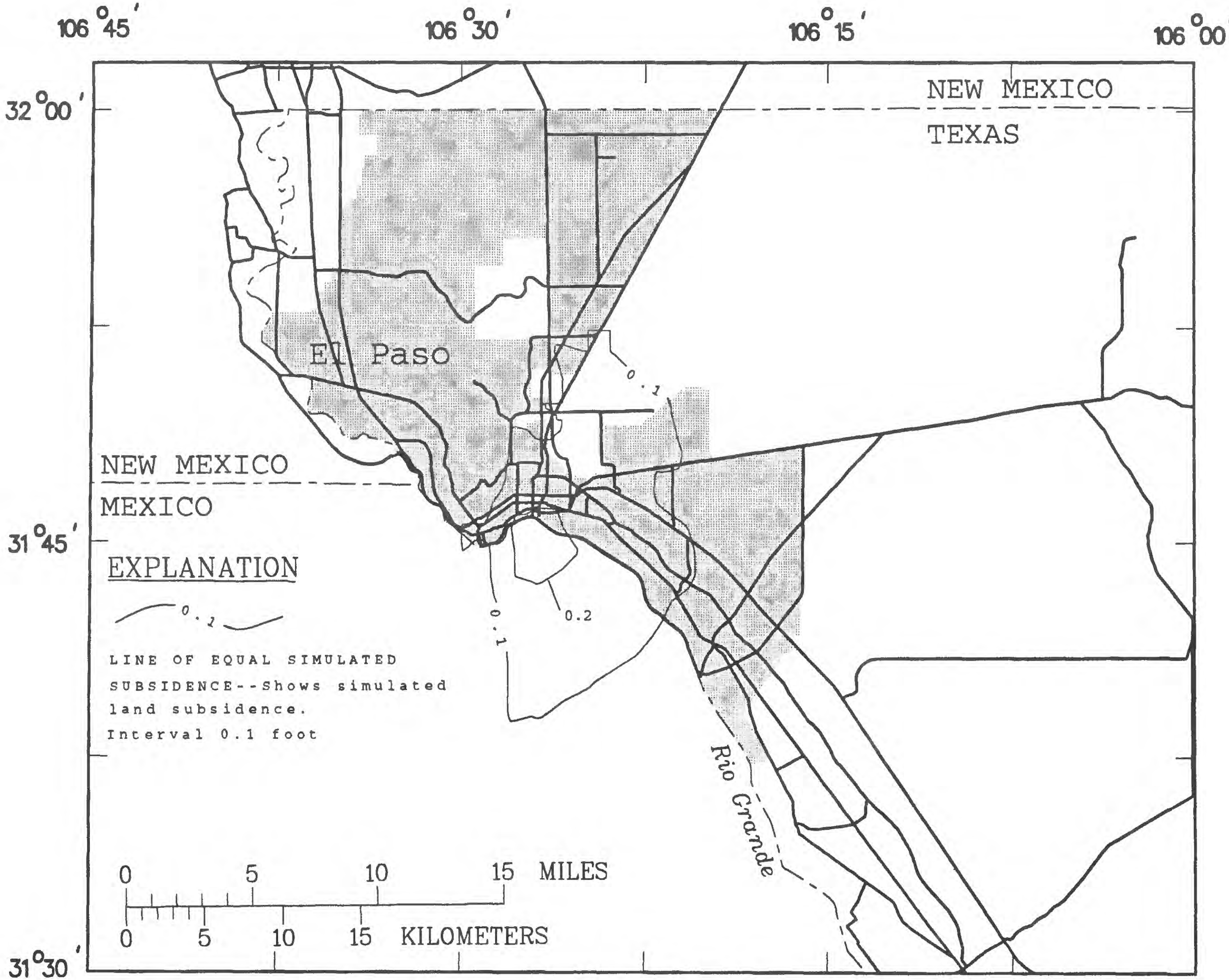

Figure 9.--Projected net increase in land subsidence between 1984 and 1992.

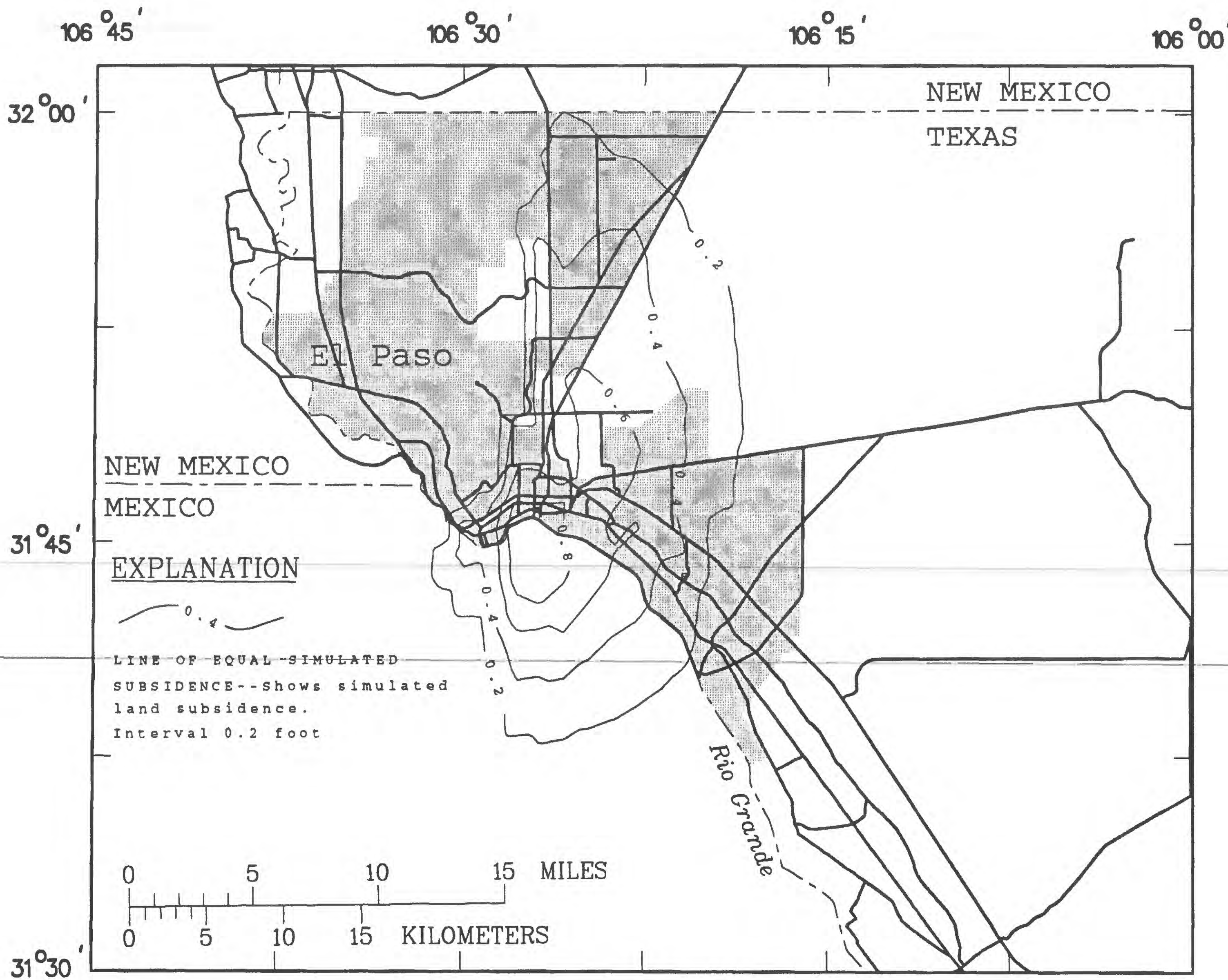

Figure 10.--Projected total land subsidence from 1880 to 2000 with the proposed diversion of flow from the Rio Grande.

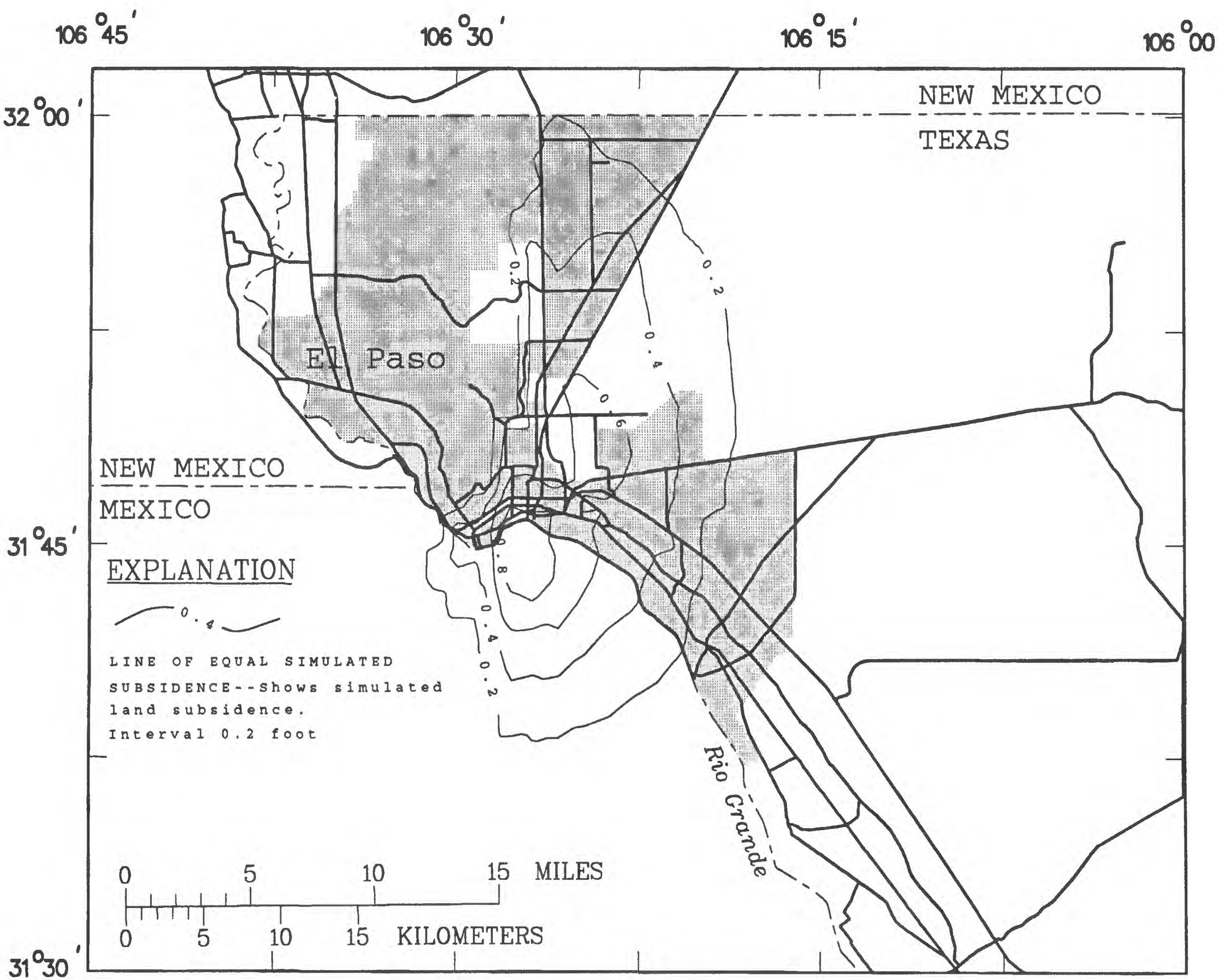

Figure 11.--Projected total land subsidence from 1880 to 2000 without the proposed diversion of flow from the Rio Grande.

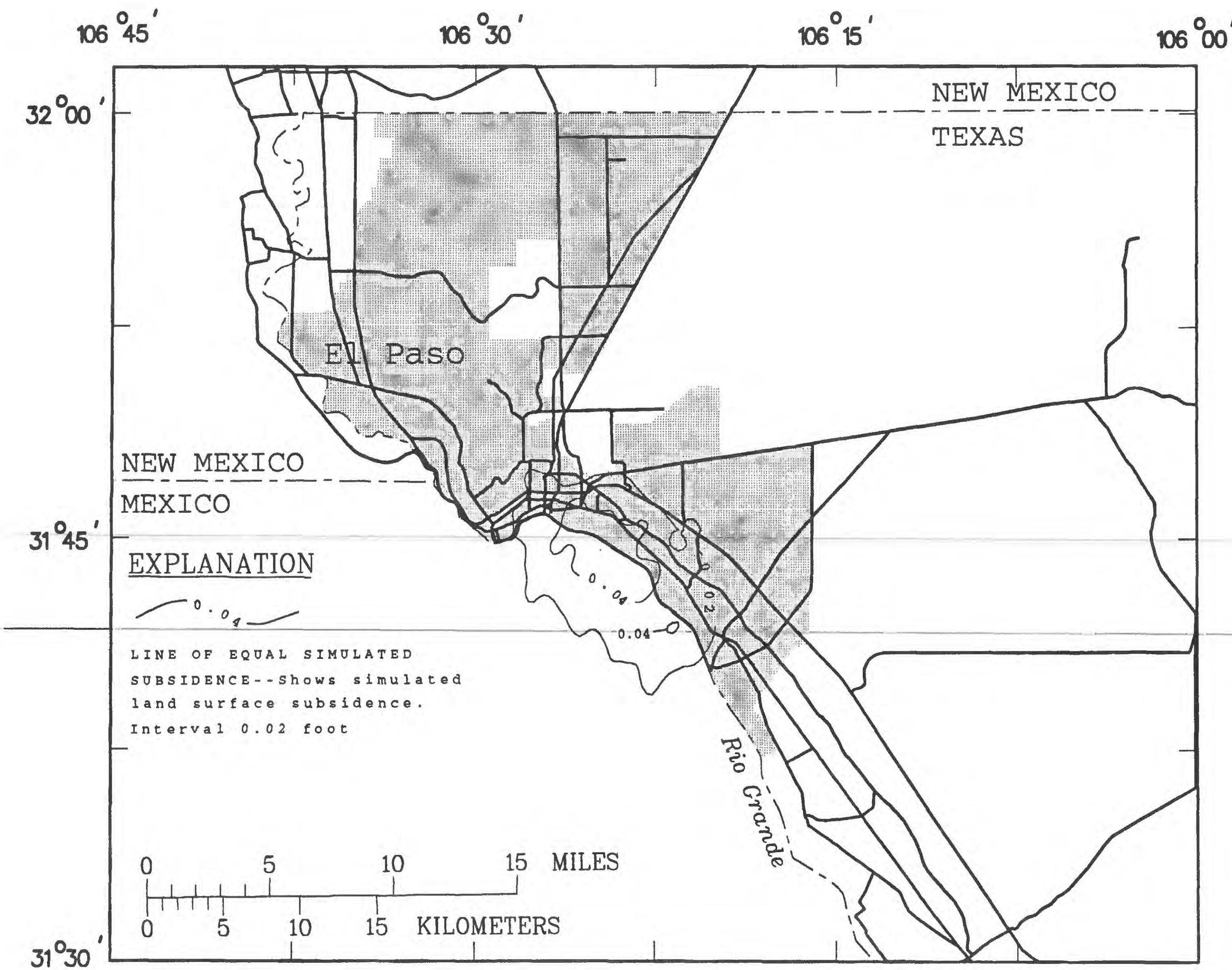

Figure 12.--Projected net increase in land subsidence between 1992 and 2000 that might occur as a result of the proposed diversion of flow from the Rio Grande.

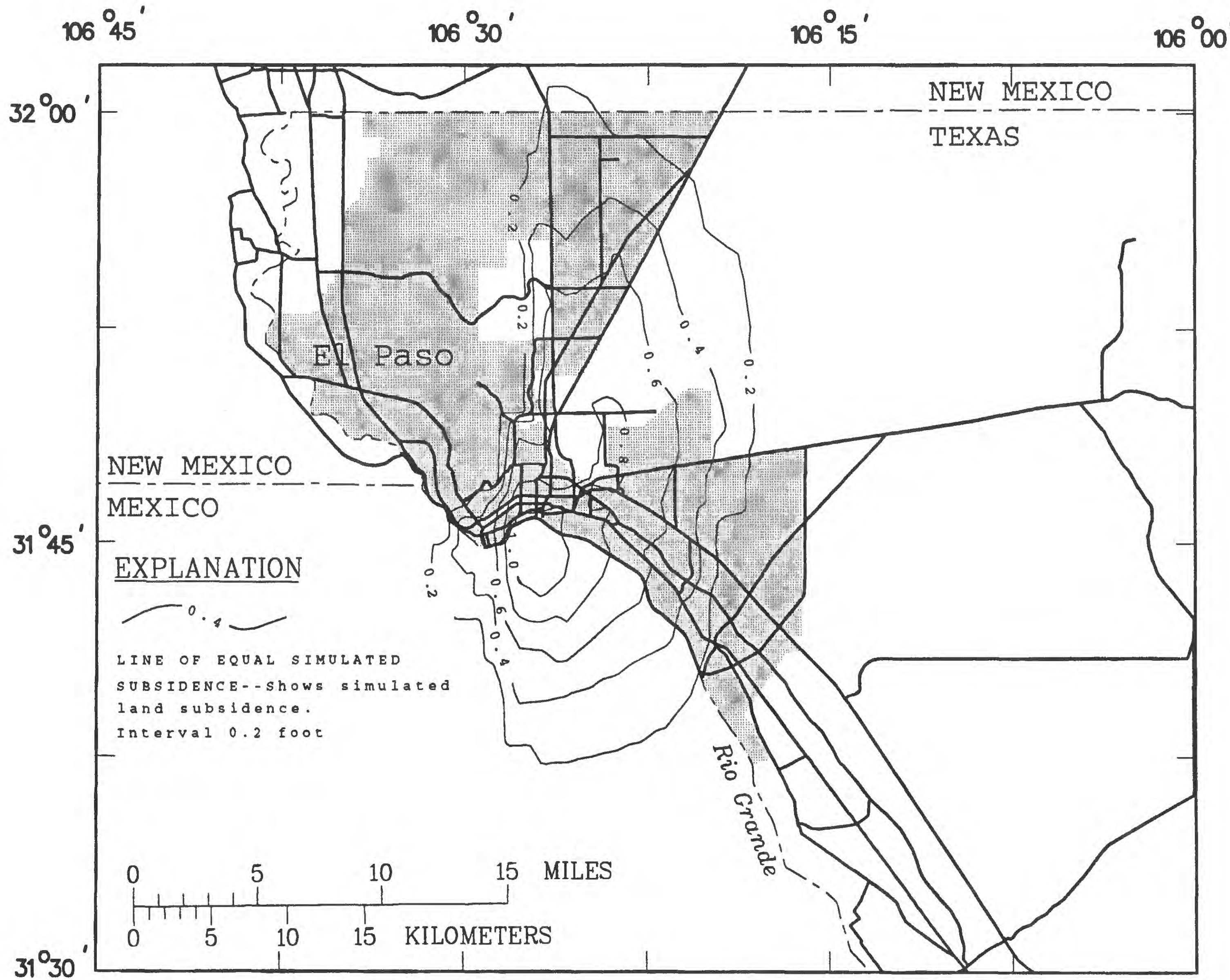

Figure 13.--Projected total land subsidence from 1880 to 2010 with the proposed diversion of flow from the Rio Grande.

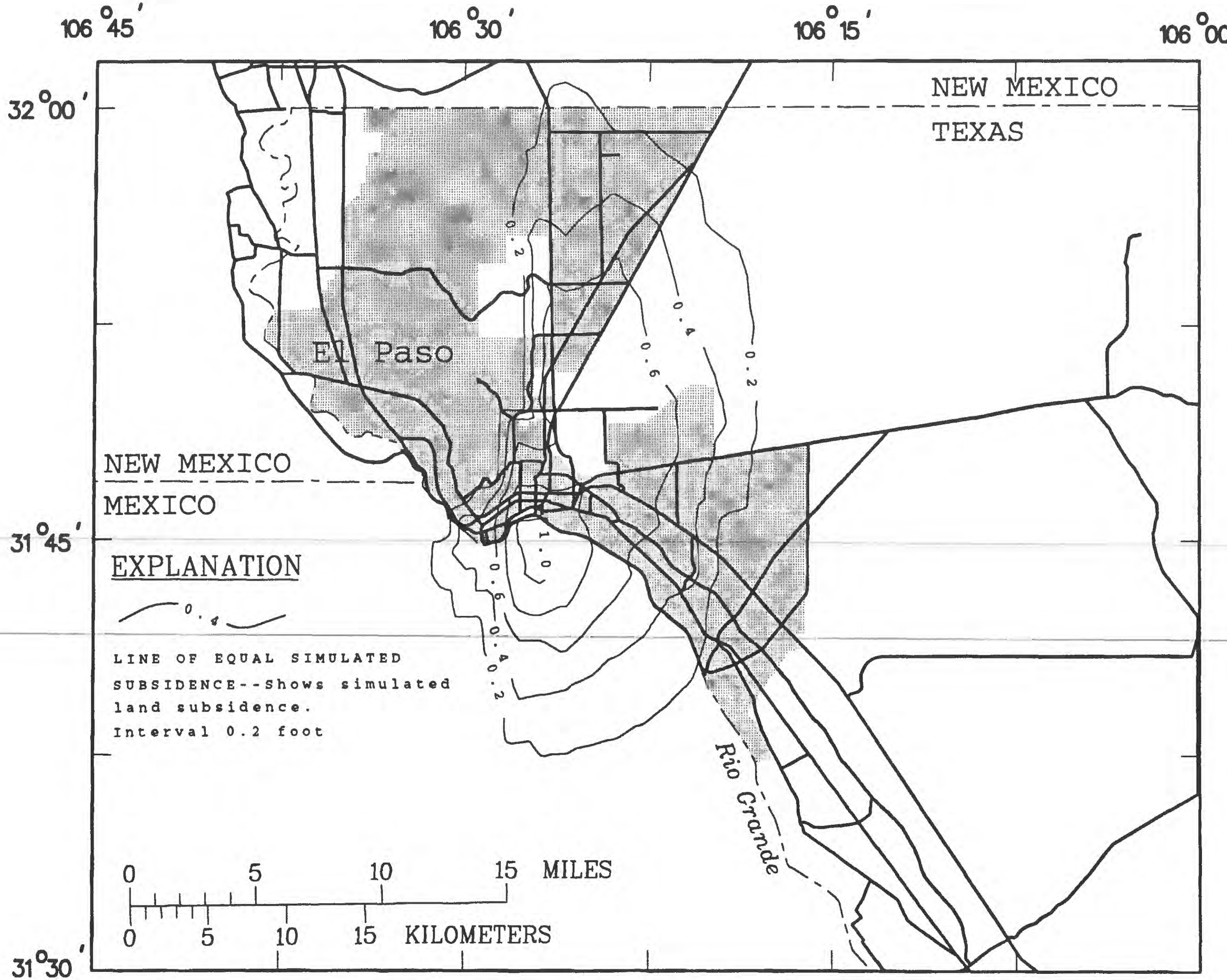

Figure 14.--Projected total land subsidence from 1880 to 2010 without the proposed diversion of flow from the Rio Grande.

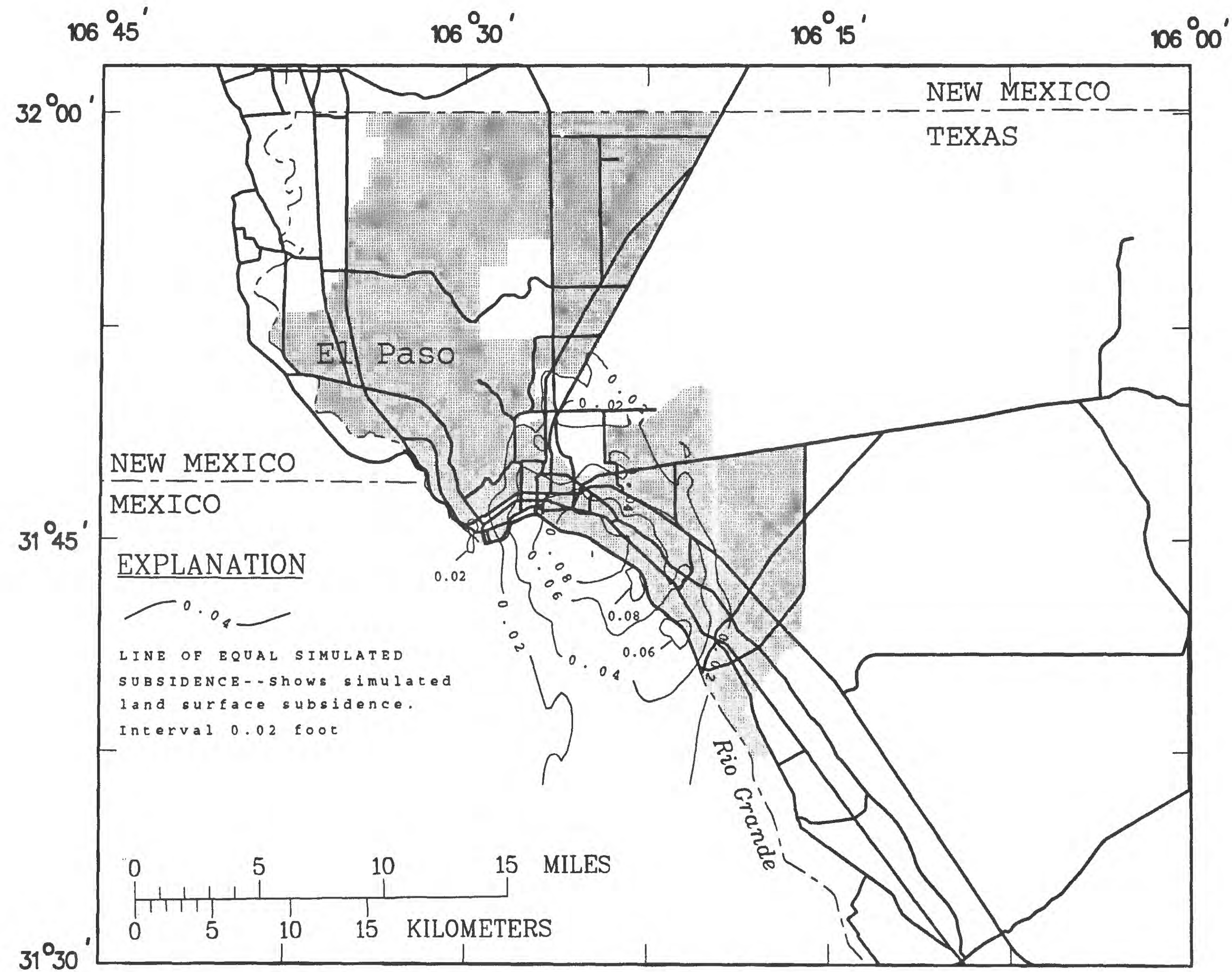

Figure 15.--Projected net increase in land subsidence between 1992 and 2010 that might occur as a result of the proposed diversion of flow from the Rio Grande.

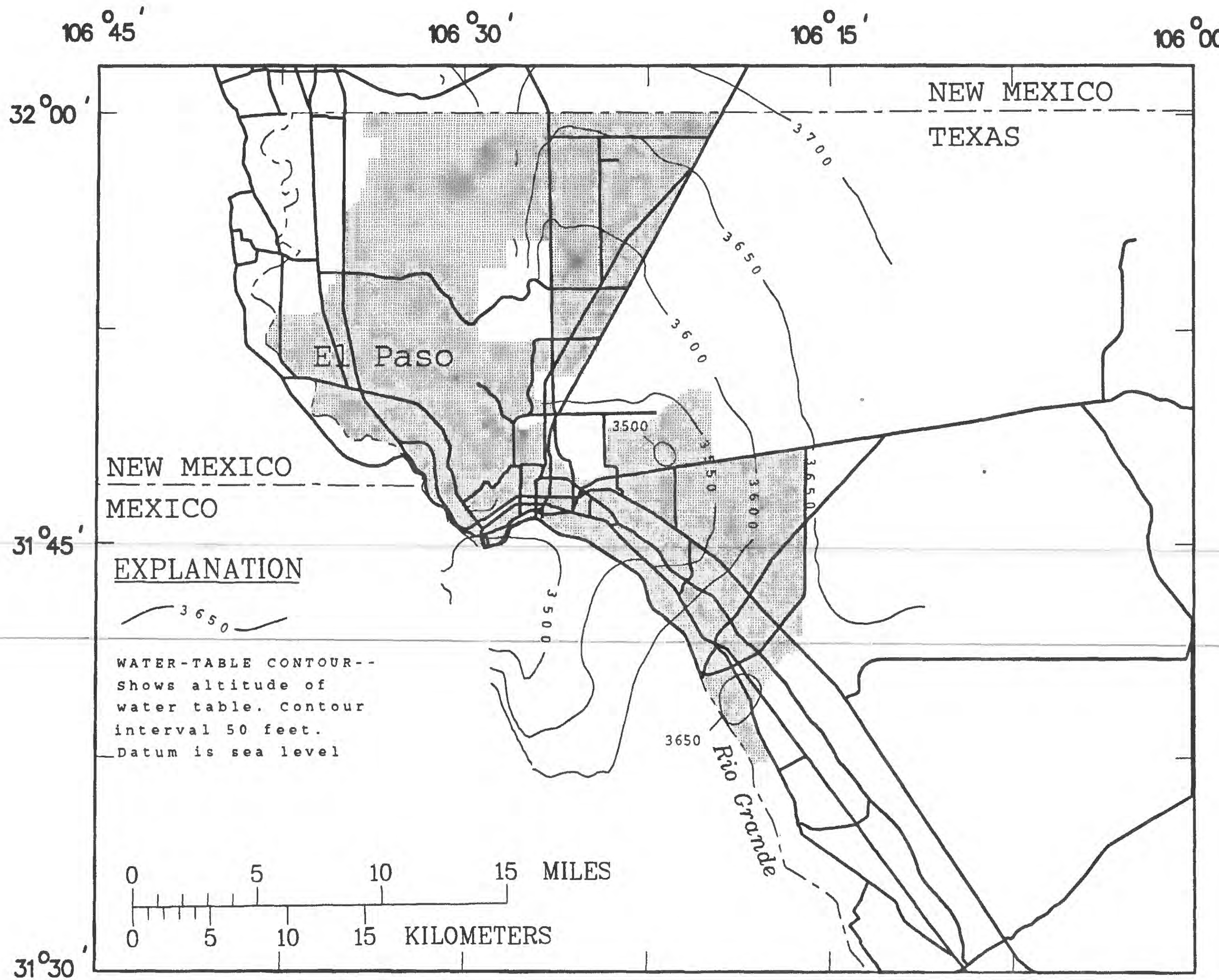

Figure 16.--Projected water-table altitude for the year 2010 with the proposed diversion of flow from the Rio Grande.

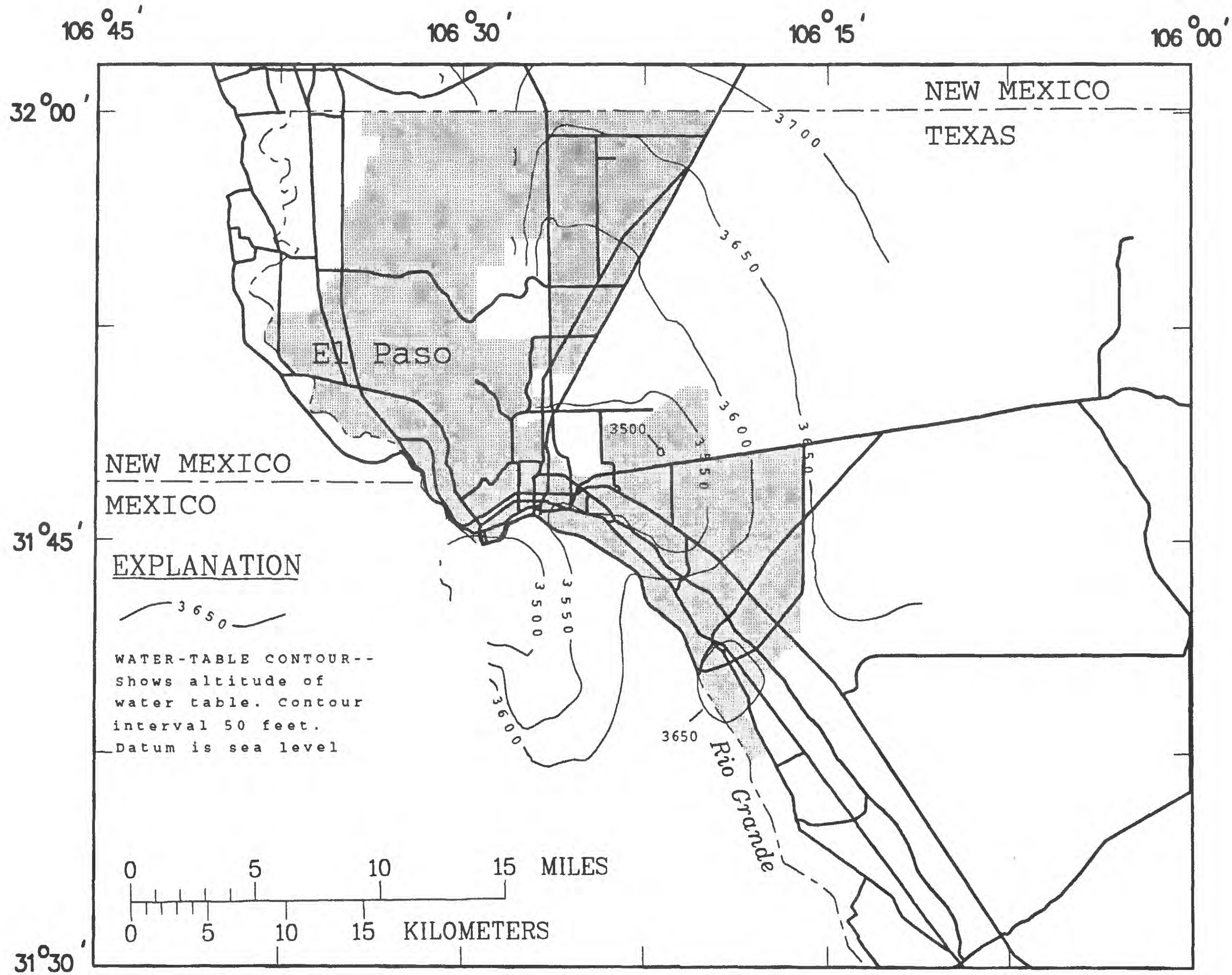

Figure 17.--Projected water-table altitude for the year 2010 without the proposed diversion of flow from the Rio Grande.

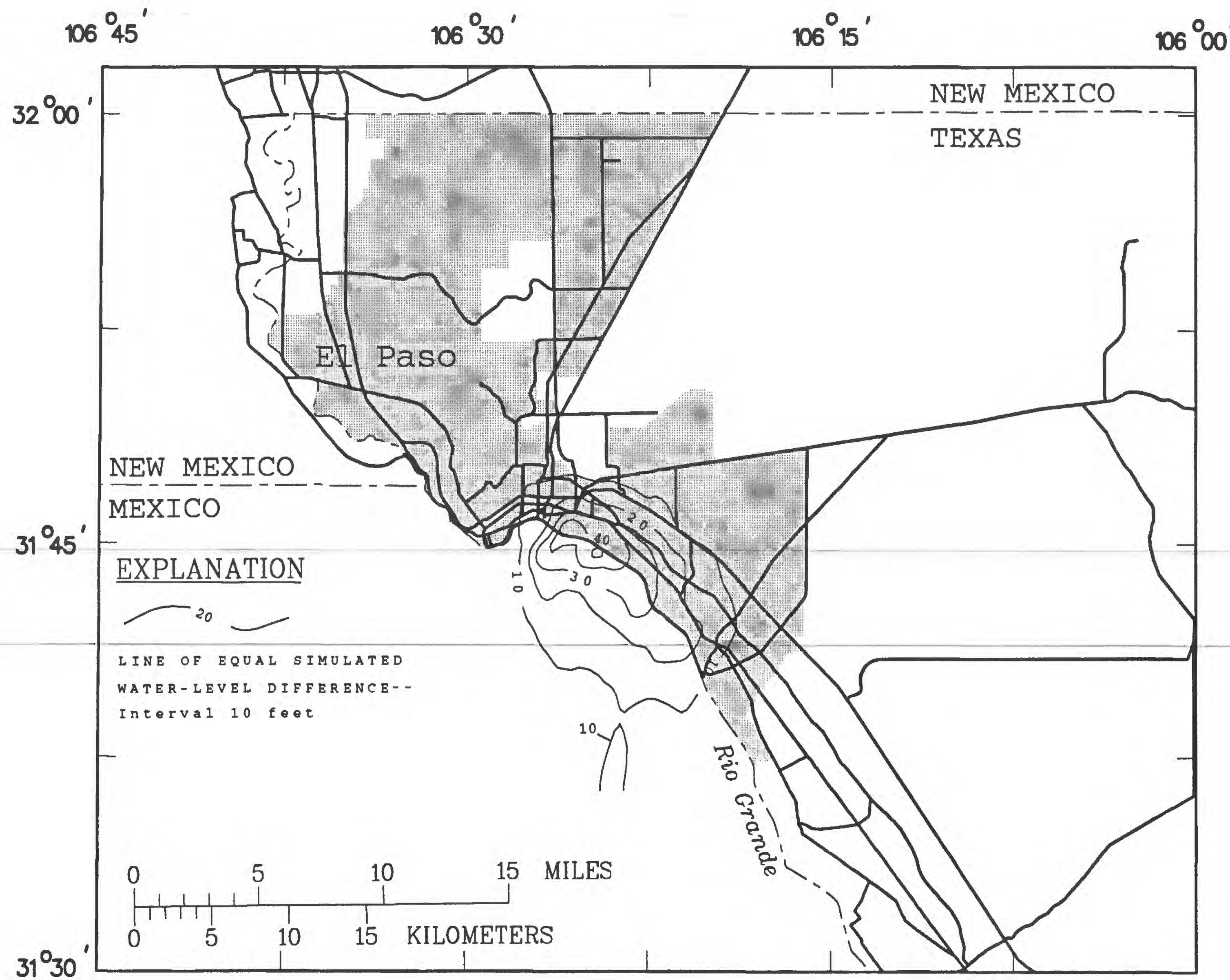

Figure 18.--Projected net decline in water-table altitude between 1992 and 2010 that might occur as a result of the proposed diversion of flow from the Rio Grande.

RESULTS OF SIMULATIONS

Because of the relatively large dimensions of the finite-difference model cells in the vicinity of the simulated Rio Grande (fig. 3), the simulated subsidence was much more smoothly averaged and distributed than the reported subsidence. The closest cell spacing, and hence the highest degree of resolution of the model, is 1 mile. The cell spacing increases to as much as 3 miles in the area of simulated diversion of flow. The subsidence model documented in this report is not capable of simulating localized differential subsidence of the sort that might cause damage to roads or other structures, as documented by Land and Armstrong (1985).

The benchmark flow model and the subsidence model showed a rate of recharge of 33,000 acre-feet from the Rio Grande to the aquifer system during 1983, increasing to 35,200 acre-feet by 1992. These amounts compare favorably with Land and Armstrong's (1985) estimate of 30,000 acre-feet for 1983. Simulations indicate that the proposed diversion of flow from the reach of the Rio Grande would reduce this recharge to about 14,000 acre-feet in 1992.

With the exception noted below, there was no indication that the storage coefficient of compressible material had made the transition from elastic to inelastic by 1984. The specific yield under water-table conditions so dominates the total storage coefficient that perhaps the only way to detect the transition is by monitoring for an increase in the rate of subsidence.

The average rate of subsidence per unit change in potentiometric head for all of the uppermost active model cells where subsidence was simulated was computed to be 4.2×10^{-3} for the additional subsidence (fig. 15) and drawdown (fig. 18) that were simulated to result from the proposed diversion. This value corresponds well with the elastic rate reported for south-central Arizona in table 1. However, the maximum simulated rate was 2.0×10^{-2} and a significant number of cells exceeded 1.0×10^{-2}. These high rates may be due to locally large thickness of compressible material.

The amounts of land subsidence that were simulated to be a result of the diversion of flow from the Rio Grande generally were less that 0.06 foot by 2000 (fig. 12), and 0.1 foot by 2010 (fig. 15). These maxima are, however, localized and more typical amounts of simulated subsidence are less than 0.04 and 0.06 foot for each respective time. The maximum total subsidence that is projected to occur without diversion of flow from the Rio Grande is slightly more than 0.8 foot for 2000 (fig. 11) and slightly more than 1.0 foot for 2010 (fig. 14). The simulated increase in drawdown that would be associated with the proposed diversion of flow was 50 feet or less (fig. 18).

The margin of error of the coupled flow and subsidence model is relatively minor through 1983 but is unknown for more recent time. The use of a storage-coefficient value typical of elastic deformation and compression appears to account for known subsidence through 1983. How the aquifer system will respond if and when it reaches the conditions matching the preconsolidation stress of the system remains unknown.

FUTURE STUDY NEEDS

Land and Armstrong (1985, p. 51) recommended three courses of investigation beyond the scope of their study: a numerical model to address localized differential subsidence and reactivation of faults; a monitoring program to document subsidence; and the development of an engineering tool to "determine the proportion of subsidence that can be attributed to a water-resources development or management action." These recommendations are still applicable. In addition, one or more extensometers might be constructed to monitor the rate of interbed compaction.

The subsidence model presented in this report appeared to perform well even though the flow model that was its numerical foundation was not designed for a detailed analysis of the aquifer system in the vicinity of the Rio Grande. The focus of the flow model was on withdrawals and aquifer development along the east flank of the Franklin Mountains; the simulated Rio Grande boundary with its expanded model cell dimensions was of secondary interest. A model designed to simulate subsidence would place great detail in the area of the Rio Grande and the network of canals and drains.

Land and Armstrong (1985) suggested the establishment of a network of regularly reoccupied vertical-control stations. The Global Positioning Systems (GPS) technology currently is a very practical, fast, and economical method of obtaining very precise measurements of geographic and vertical coordinates. The subsidence model documented in this report is limited by the lack of recent information regarding land subsidence. This deficiency could be solved, in part, by releveling of the reference points and benchmarks cited in Land and Armstrong (1985) and expanding the network of reference points.

Finally, the construction of one or more extensometers would allow the analytical determination of the amount of interbed compaction and the coefficient of elastic storage of the compressible materials in the aquifer. The extensometers could also be used to monitor for the onset of inelastic compression in the aquifer system and eventually to calculate its magnitude.

SUMMARY

An existing finite-difference ground-water-flow model prepared for the City of El Paso was used as the basis for a numerical model of interbed compaction and land subsidence. Care was taken to avoid altering the flow and potentiometric-head calibration of the existing model while calibrating the simulated subsidence to the recorded subsidence for the period from about 1954 to 1984. The model successfully replicated the reported subsidence for the period of calibration. The model's simulated elastic storage coefficient of 2.0×10^{-5} per foot was within the range normally associated with elastic deformation, as was the 4.2×10^{-3} simulated rate of subsidence per unit change in potentiometric head derived from some of the comparative simulations to 2010.

The subsidence model was used to test the potential effects of diverting the flow of the Rio Grande from a 13-mile segment of its unlined channel into a series of canals and waterways. The diversion is intended to minimize seepage loss, evaporation, and unauthorized diversions. Simulations indicated that the maximum seepage rate of 35,200 acre-feet per year just prior to 1992 would be reduced to about 14,000 acre-feet in 1992 as a result of the proposed diversion.

Assuming no significant change in the sources of municipal water and the distribution of water-supply wells, and using the projected increase in withdrawal inherent in the model prepared for the City of El Paso, the increase in drawdown in the aquifer as a result of the decreased amount of seepage to the aquifer would be a maximum of about 50 feet. Assuming that the preconsolidation stress is not exceeded, maximum land subsidence, which would be slightly more than 1 foot without the proposed diversion of flow, would be increased by slightly less than 0.1 foot in a localized area (and generally by about 0.06 foot or less) should the diversion occur.

SELECTED REFERENCES

Burns, A.W., and Hart, D.L., 1988, Simulated water-level declines caused by ground-water withdrawals near Holloman Air Force Base, Otero County, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 86-4324, 44 p.

Davis, M.E., 1967, Memorandum on availability of water having less than 2,500 parts per million dissolved solids in alluvium of Rio Grande near El Paso, Texas: U.S. Geological Survey Open-File Report, 7 p.

Davis, M.E., and Leggat, E.R., 1967, Preliminary results of the investigation of the saline-water resources in the Hueco Bolson near El Paso, Texas: U.S. Geological Survey Open-File Report, 27 p.

Domenico, P.A., and Mifflin, M.D., 1965, Water from low-permeability sediments and land subsidence: Water Resources Research, v. 1, no. 4, p. 563-576.

Holzer, T.L., 1981, Preconsolidation stress of aquifer systems in areas of induced land subsidence: Water Resources Research, v. 17, no. 3, p. 693-704.

Kelly, T.E., and Hearne, G.A., 1976, The effects of ground-water development on the water supply in the Post Headquarters area, White Sands Missile Range, New Mexico: U.S. Geological Survey Open-File Report 76-277, 96 p.

Kernodle, J.M., 1992, Summary of ground-water-flow models of basin-fill aquifers in the Southwestern Alluvial Basins region, Colorado, New Mexico, and Texas: U.S. Geological Survey Open-File Report 90-361, 81 p.

Knowles, D.B., and Kennedy, R.A., 1958, Ground-water resources of the Hueco Bolson, northeast of El Paso, Texas: U.S. Geological Survey Water-Supply Paper 1426, 186 p.

Knowles, T.R., and Alvarez, H.J., 1979, Simulated effects of ground-water pumping in portions of the Hueco Bolson in Texas and Mexico during the period 1973 through 2029: Texas Department of Water Resources Report LP-104, 26 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.

Laney, R.L., 1976, Water-level declines, land subsidence, and earth fissures in south-central Arizona: Arizona Water Commission Report 8, 9 p.

Leake, S.A., 1990, Interbed storage changes and compaction in models of regional groundwater flow: Water Resources Research, v. 26, no. 9, p. 1939-1950.

_____1991, Simulation of vertical compaction in models of regional ground-water flow: Proceedings of the Fourth International Symposium on Land Subsidence, IAHS Publication no. 200, p. 565-574.

Leake, S.A., and Prudic, D.E., 1988, Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 88-482, 80 p.

Lee Wilson and Associates, 1985a, Report 3--Hydrogeology of the Hueco Bolson: prepared for the Public Services Board, City of El Paso, Texas.

_____1985b, Report 4--Technical framework for evaluation of proposed Hueco Basin appropriations: prepared for the Public Services Board, City of El Paso, Texas.

Leggat, E.R., and Davis, M.E., 1966, Analog model study of the Hueco Bolson near El Paso, Texas: Texas Water Development Board Report 28, 25 p.

Lovejoy, E.M.P., and Hawley, J.W., 1978, El Paso to New Mexico-Texas State line, in Guidebook to Rio Grande rift in New Mexico and Colorado: Socorro, New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 57-68.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

Meyer, W.R., 1976, Digital model for simulated effects of ground-water pumping in the Hueco Bolson, El Paso area, Texas, New Mexico, and Mexico: U.S. Geological Survey Water-Resources Investigations Report 58-75, 31 p.

Orr, B.R., and Risser, D.W., in press, Geohydrology and potential effects of development of freshwater resources in the northern part of the Hueco Bolson, Doña Ana and Otero Counties, New Mexico, and El Paso County, Texas: U.S. Geological Survey Water-Resources Investigations Report 91-4082.

Risser, D.W., 1988, Simulated water-level and water-quality changes in the bolson-fill aquifer, Post Headquarters area, White Sands Missile Range, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 87-4152, 69 p.

Sayre, A.N., and Livingston, Penn, 1945, Ground-water resources of the El Paso area, Texas: U.S. Geological Survey Water-Supply Paper 919, 190 p.

Terzaghi, K., 1936, The shearing resistance of saturated soils: Proceedings of the First International Conference on Soil Mechanics, no. 1, p. 54-56.

Terzaghi, K., and Peck, R.B., 1948, Soil mechanics in engineering practice: New York, John Wiley and Sons, p. 64-65.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: American Geophysical Union Transactions, v. 16, p. 519-524.

White, D.E., 1983, Summary of hydrologic information in the El Paso, Texas, area, with emphasis on Ground-water studies, 1903-80: U.S. Geological Survey Open-File Report 83-775, 77 p.

White, D.E., and Sladek, G.J., 1990, Summary of data from the 1981-83 pilot study and 1985-89 operations of the Hueco Bolson recharge project, northeast El Paso, Texas: U.S. Geological Survey Open-File Report 90-175, 38 p.