Simulated Ground-Water Flow in the Hueco Bolson, an Alluvial-Basin Aquifer System near El Paso, Texas

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

Water-Resources Investigations Report 02-4108

Prepared in cooperation with
EL PASO WATER UTILITIES
and the
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By Charles E. Heywood and Richard M. Yager

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Albuquerque, New Mexico
2003

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CONVERSION FACTORS, ABBREVIATIONS, AND DATUMS

Multiply	By	To obtain
centimeter (cm)	0.06102	inch (in.)
millimeter	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
square kilometer (km^2)	247.1	acre
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter per day (m^3/d)	0.0004087	cubic foot per second (ft^3/s)
cubic meter per day (m^3/d)	0.2961	acre-foot per year (acre-ft/yr
cubic meter per day (m^3/d)	96,489	gallons per year (gal/yr)
acre-foot (acre-ft)	1,233	cubic meter (m^3)

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

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.

SIMULATED GROUND-WATER FLOW IN THE HUECO BOLSON, AN ALLUVIAL-BASIN AQUIFER SYSTEM NEAR EL PASO, TEXAS

By Charles E. Heywood and Richard M. Yager

ABSTRACT

The neighboring cities of El Paso, Texas, and Ciudad Juarez, Chihuahua, Mexico, have historically relied on ground-water withdrawals from the Hueco Bolson, an alluvial-aquifer system, to supply water to their growing populations. By 1996, ground-water drawdown exceeded 60 meters in some areas under Ciudad Juarez and El Paso.

A simulation of steady-state and transient ground-water flow in the Hueco Bolson in westernmost Texas, south-central New Mexico, and northern Chihuahua, Mexico, was developed using MODFLOW-96. The model is needed by El Paso Water Utilities to evaluate strategies for obtaining the most beneficial use of the Hueco Bolson aquifer system. The transient simulation represents a period of 100 years beginning in 1903 and ending in 2002. The period 1903 through 1968 was represented with 66 annual stress periods, and the period 1969 through 2002 was represented with 408 monthly stress periods.

The ground-water flow model was calibrated using MODFLOWP and UCODE. Parameter values representing aquifer properties and boundary conditions were adjusted through nonlinear regression in a transient-state simulation with 96 annual time steps to produce a model that approximated (1) 4,352 water levels measured in 292 wells from 1912 to 1995, (2) three seepage-loss rates from a reach of the Rio Grande during periods from 1979 to 1981, (3) three seepage-loss rates from a reach of the Franklin Canal during periods from 1990 to 1992, and (4) 24 seepage rates into irrigation drains from 1961 to 1983. Once a calibrated model was obtained with MODFLOWP and UCODE, the optimal parameter set was used to create an equivalent MODFLOW-96 simulation with monthly temporal discretization to improve computations of seepage from the Rio Grande and to define the flow field for a chloride-transport simulation.

Model boundary conditions were modified at appropriate times during the simulation to represent changes in well pumpage, drainage of agricultural fields, and channel modifications of the Rio Grande. The model input was generated from geographic information system databases, which facilitated rapid model construction and enabled testing of several conceptualizations of hydrogeologic facies boundaries. Specific yield of unconfined layers and hydraulic conductance of Quaternary faults in the fluvial facies were the most sensitive model parameters, suggesting that ground-water flow is impeded across the fault planes.

INTRODUCTION

The neighboring cities of El Paso, Texas, and Ciudad Juarez, Chihuahua, Mexico, have historically relied on ground-water withdrawals from the Hueco Bolson, an alluvial-aquifer system, to supply water to their growing populations. At the end of the 20th century, about 680,000 people lived in the El Paso metropolitan area (U.S. Department of Commerce, 2002) and the total population (including Ciudad Juarez) was about 2 million. The term “bolson,” literally meaning “handbag” or “purse” in Spanish, is local terminology that may be considered synonymous with “basin.” The Hueco Bolson is considered the southern portion of the Tularosa-Hueco Basin. The term “Tularosa Basin” is used for the northern portion, which lies entirely in the State of New Mexico and is not modeled in this study.

In the United States, diversions from the Rio Grande and ground-water withdrawals from the Mesilla Basin (west of the study area) also supply the freshwater demands of the military, industries, and public in the El Paso area. In Mexico, diversions from the Rio Grande are used for agriculture; water needed by Ciudad Juarez is supplied solely by extraction from the Hueco Bolson. By 1996, ground-water drawdown exceeded 60 m in some areas under Ciudad Juarez and El Paso. Fresh ground water stored in the aquifer system beneath these cities is bordered by regions of brackish to saline ground water. As water levels in the freshwater portions of the aquifer declined, intrusion of the surrounding brackish water degraded water quality in public supply wells, which sometimes required well abandonment.

Prior to human intervention, infiltration of water from the Rio Grande was the dominant mechanism of aquifer-system recharge in the El Paso area. During the 20th century, numerous diversions from the Rio Grande affected the distribution of this potential recharge water. A section of the Rio Grande between downtown El Paso and Ciudad Juarez was converted to a lined canal in 1968, which prevented subsequent recharge from the river to the ground-water system along that section. This decreased recharge exacerbated the effect of increased ground-water withdrawals, increasing the rate of ground-water-level declines (Land and Armstrong, 1985).

Purpose and Scope

This report describes the hydrogeology of the Hueco Bolson and documents a transient ground-water flow model of the Hueco Bolson. The model, developed in cooperation with El Paso Water Utilities (EPWU) and the U.S. Army at Fort Bliss, is needed by the EPWU to evaluate strategies for obtaining the most beneficial use of the Hueco Bolson aquifer system. Included in the report are a (1) description of the hydrogeologic features relevant to the numerical simulation, (2) summary of the computer codes used for the simulations, (3) description of the model-calibration procedure, and (4) discussion of the results of the steady-state and transient simulations, including estimation of seepage loss with a specified design flow in the Rio Grande and no diversion to the American Canal Extension (ACE). Modifications to MODFLOWP and MODFLOW are presented in two appendixes.

The active model area encompasses 5,303 km^2 (2,408 mi^2) in Mexico and the United States, extending from 37 km north of the New Mexico-Texas State boundary to a point on the Rio Grande 3 km south of Fort Hancock, Texas, 79 km southeast of El Paso. Model boundaries represent the perimeter of Hueco Bolson deposits throughout most of the modeled area and coincide with the Franklin and Organ Mountains to the west and the Hueco Mountains to the east in the United States, and the Sierra Juarez, Sierra El Presidio, and Sierra Guadalupe to the west and south in Mexico (figs. 1 and 2).

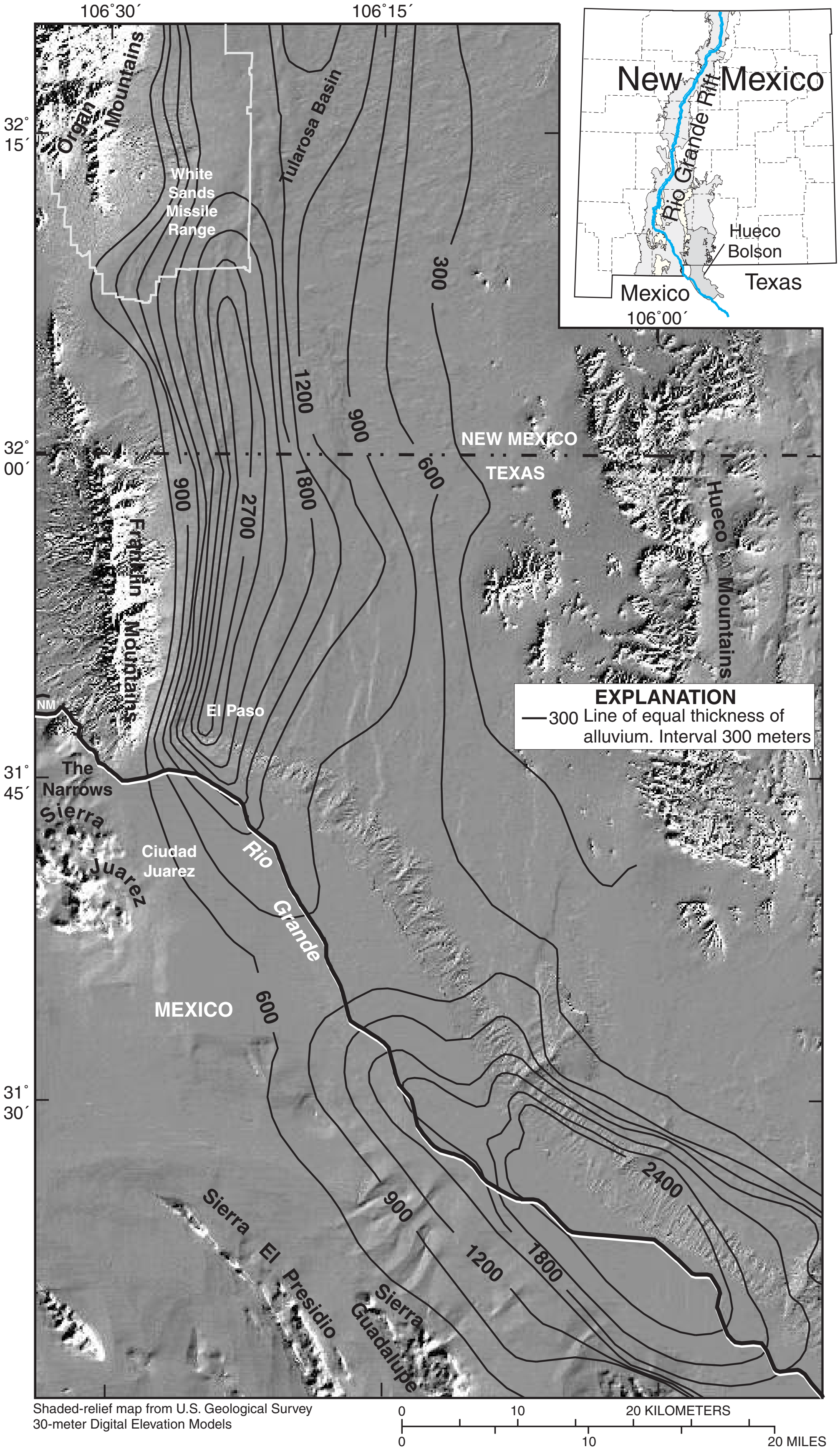
Previous Investigations

Sayre and Livingston (1945) first provided a comprehensive overview of ground-water resources in the El Paso area. Several ground-water flow models have been developed to investigate the effects of pumping on water levels and salinity in the Hueco Bolson. Leggat and Davis (1966) constructed an electric analog model to predict ground-water drawdowns through 1990 resulting from proposed ground-water withdrawals. A two-layer transient model by Meyer (1976) represented freshwater with a dissolved-solids concentration less than 1,000 milligrams per liter in both alluvial and bolson deposits. The model was used to estimate the total volume of freshwater in storage and to simulate water-level declines resulting from planned ground-water withdrawals from 1973 to 1991.

Lee Wilson and Associates (1985a,b; 1991) developed a four-layer model using MODFLOW in which layer thickness corresponded to the presumed thickness of water-quality zones. Kernodle (1992) used the Lee Wilson and Associates (1985a,b) model to estimate additional elastic aquifer compaction that might result from diverting flow in a segment of the Rio Grande into an extension of the American Canal. Groschen (1994) developed a four-layer model using MODFLOW and HST3D (Kipp, 1987) to simulate the movement of saline water in response to ground-water withdrawal and concluded that increased salinity in wells screened in the bolson deposits was caused by leakage from the overlying alluvial aquifer.

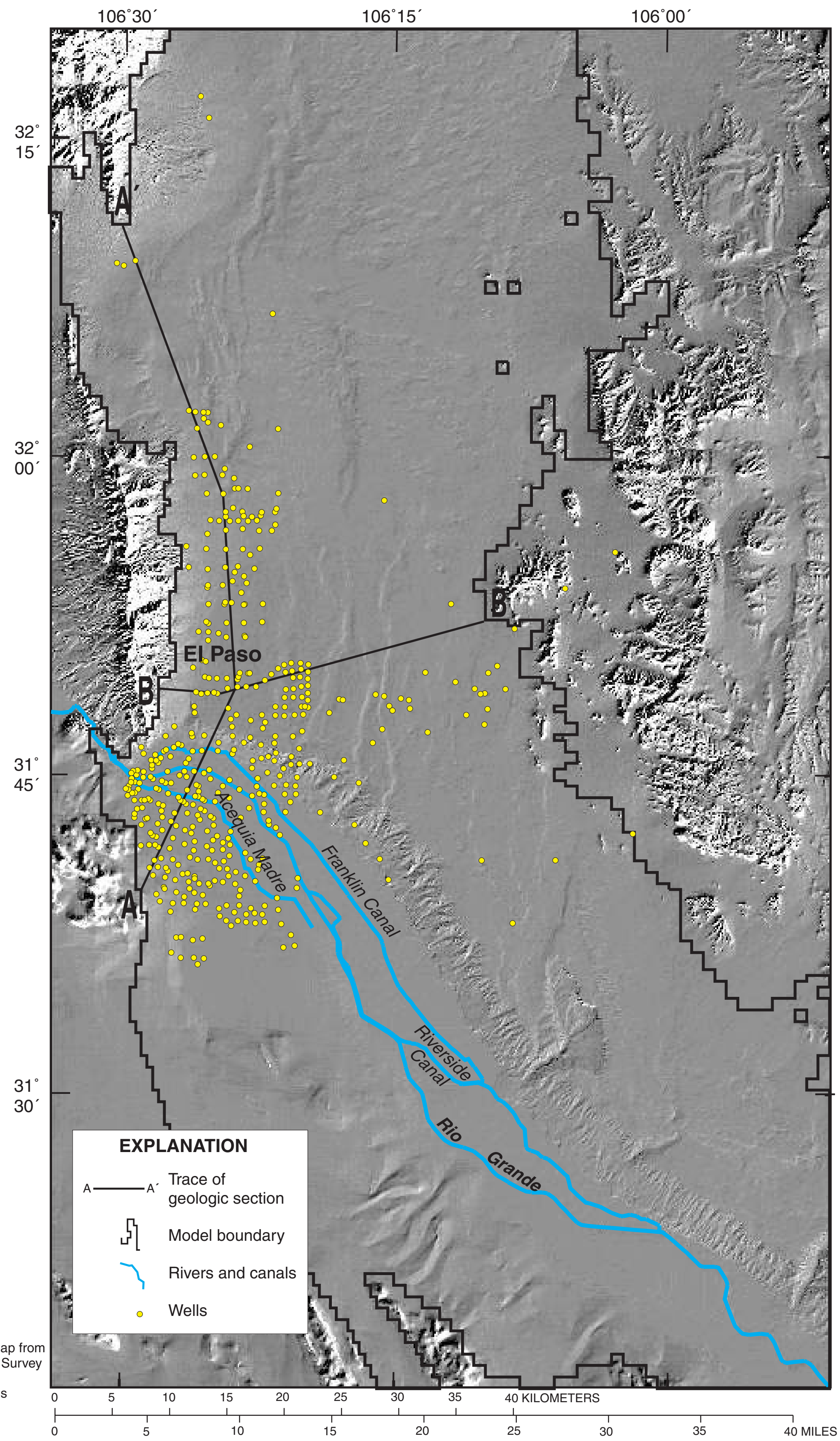
HYDROGEOLOGY OF THE HUECO BOLSON

The Hueco Bolson is a fault-bounded structural depression associated with the Rio Grande Rift (fig. 1). At the inception of Rio Grande rifting about 26 million years ago (Chapin and Seager, 1975), normal faults accommodated regional extension, resulting in downdropped structural grabens. Igneous rocks of Precambrian age and sedimentary rocks of Paleozoic and Mesozoic age surround and underlie the Hueco Bolson. Unconsolidated to poorly consolidated deposits of Tertiary and Quaternary age consisting primarily of gravel, sand, silt, and clay have filled the basin. These deposits compose the alluvial-aquifer system known as the Hueco Bolson.



Shaded-relief map from U.S. Geological Survey 30-meter Digital Elevation Models

Figure 1. Principal physiographic features and thickness of alluvial deposits in the Hueco Bolson.



Shaded-relief map from U.S. Geological Survey 30-meter Digital Elevation Models

Figure 2. Ground-water flow-model domain, location of wells, and trace of geologic sections shown in figure 3.

Extent and Thickness of Hydrogeologic Facies

The alluvial deposits that make up the Hueco Bolson can be classified into four hydrogeologic facies (collectively, the bolson-fill facies) on the basis of their depositional processes and resulting sedimentary structures:

(1) Fluvial facies. From 3.8 million to 0.67 million years ago, the ancestral Rio Grande meandered south along the east side of the Franklin Mountains, depositing a thick sequence of fluvial sediments consisting of fine- to coarse-grained channel sand interbedded with silt and clay overbank deposits. The predominant geologic formation in this facies is the Camp Rice Formation (Strain, 1969) of Tertiary and Quaternary age. Electric logs of 101 wells in the El Paso area indicate that the fraction of clay interbeds within the freshwater portion of this facies is approximately one-third.

(2) Alluvial-fan facies. Alluvial fans originating from the present-day Organ and Franklin Mountains and Sierra Juarez consist of poorly sorted gravel and coarse- to fine-grained sand. Deposits of this facies interfinger with the fluvial deposits of the Rio Grande.

(3) Lacustrine-playa facies. Thick deposits of clay and silt exist in the east and southeast parts of the Hueco Bolson and at depth beneath the fluvial and alluvial-fan facies. These fine-grained sediments were deposited in a low-energy environment, possibly a lake of mid-Cenozoic age that formed a terminal depocenter for the ancestral Rio Grande (Strain, 1969). The predominant geologic formation of this facies is the Tertiary Fort Hancock Formation.

(4) Recent alluvial facies. Deposition of the fluvial, alluvial-fan, and lacustrine-playa facies and subsequent erosion resulted in formation of the topographic mesa that today is east and north of El Paso (Langford, 2001). About 0.67 million years ago, the Rio Grande breached “The Narrows” (fig. 1), the gap separating the present-day Franklin Mountains from the Sierra Juarez. The Rio Grande eroded the topographic mesa, forming the present-day Rio Grande Valley. Approximately 30 to 60 m of late Pleistocene to recent sediments associated with the modern Rio Grande have been deposited in the Rio Grande Valley.

The cumulative thickness of these alluvial deposits in the Hueco Bolson is mapped in figure 1. The distribution of these facies is illustrated in the generalized geologic sections in figure 3 and in a cutaway perspective view in figure 4. The horizontal boundaries between the fluvial and lacustrine-playa facies are believed to interfinger, resulting in gradational changes in hydraulic conductivity at the scale of the ground-water flow model.

Hydraulic Conductivities

EPWU has conducted aquifer pumping tests in 85 production wells. Production wells are generally installed in known high-permeability areas, such as the alluvial-fan and fluvial facies in the Hueco Bolson. The average horizontal hydraulic conductivity estimated from these tests is 10 m/d, with a standard deviation of 7 m/d. The minimum and maximum measured horizontal hydraulic conductivities from these tests were 1 and 50 m/d, respectively.

Laboratory measurements of permeability and compressibility were made on clay core samples from five different depth intervals at a site near the Rio Grande (Harold Olsen, Colorado School of Mines, written commun., 1995). Vertical hydraulic conductivities of the undisturbed samples ranged from 6×10^{-3} to 2×10^{-2} m/d.

Ground-Water Levels

Extensive ground-water pumping from the Hueco Bolson since the 1940’s has resulted in cones of depression in the water table under El Paso and Ciudad Juarez. The observed drawdown cones generally correspond with the extent of the major production wells shown in figure 2. Total ground-water pumpage from 1903 through 1996 from the Hueco Bolson by the United States and Mexico is shown in figure 5. Ground-water withdrawals started to increase substantially during the 1950’s drought years and have increased in Mexico since the early 1970’s. Hydrographs of water levels measured in the United States and Mexico from 1935 to 1996 illustrate that ground-water levels have declined concurrently with pumpage. Examples of declining water levels in selected wells in the United States are shown in figure 6. Water quality, particularly in regard to chloride concentration, has degraded in some areas of ground-water development from 1951 to 1996 (fig. 7), such as in well 86 near the El Paso airport and well 148 in the Rio Grande Valley. In these wells, ground-water pumpage may have induced intrusion from adjacent or overlying regions of brackish water.

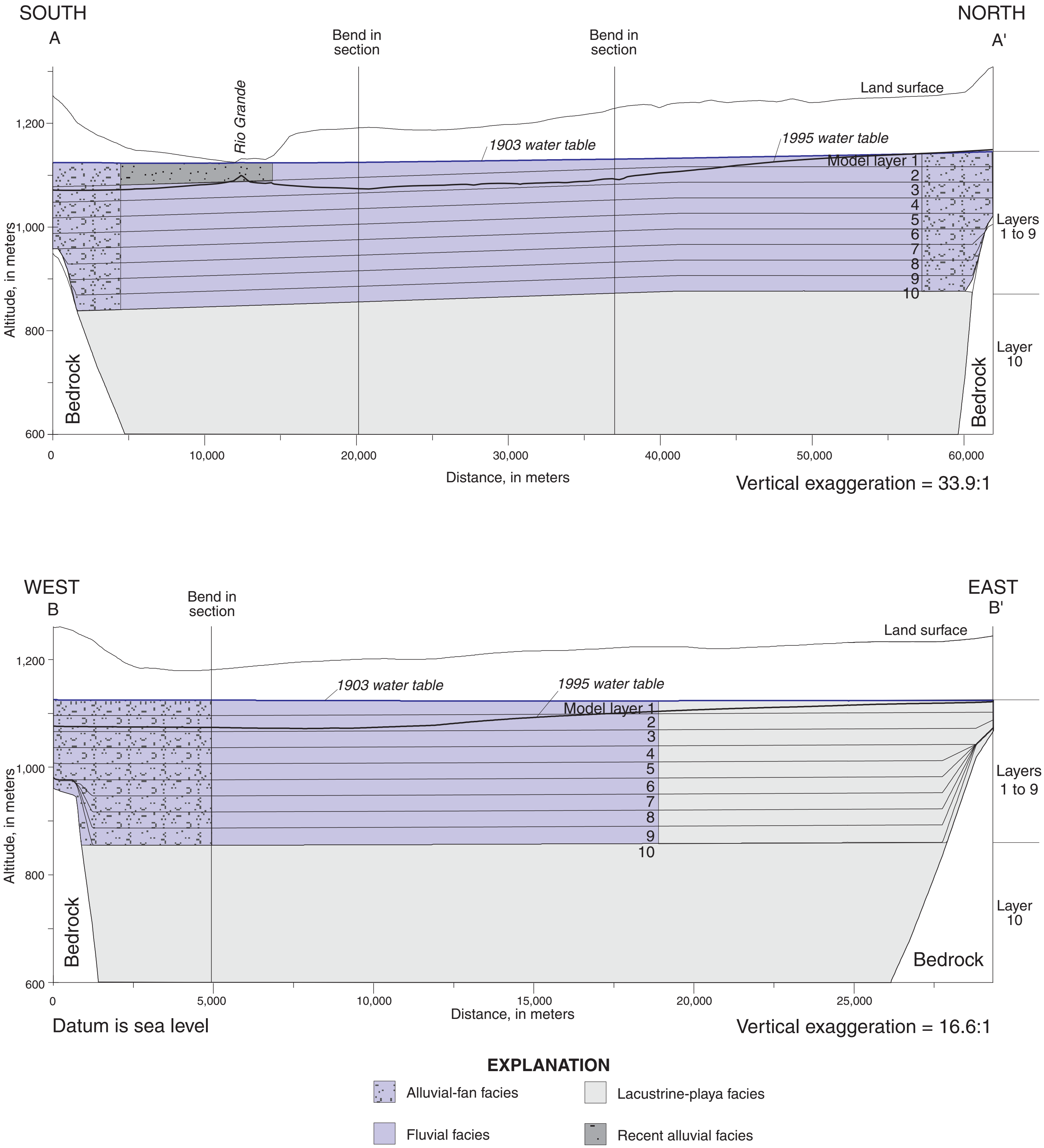


Figure 3. Generalized geologic sections A-A´ along the western margin of the Hueco Bolson and B-B´ along an east-west transect north of El Paso, Texas (trace of sections shown in figure 2).

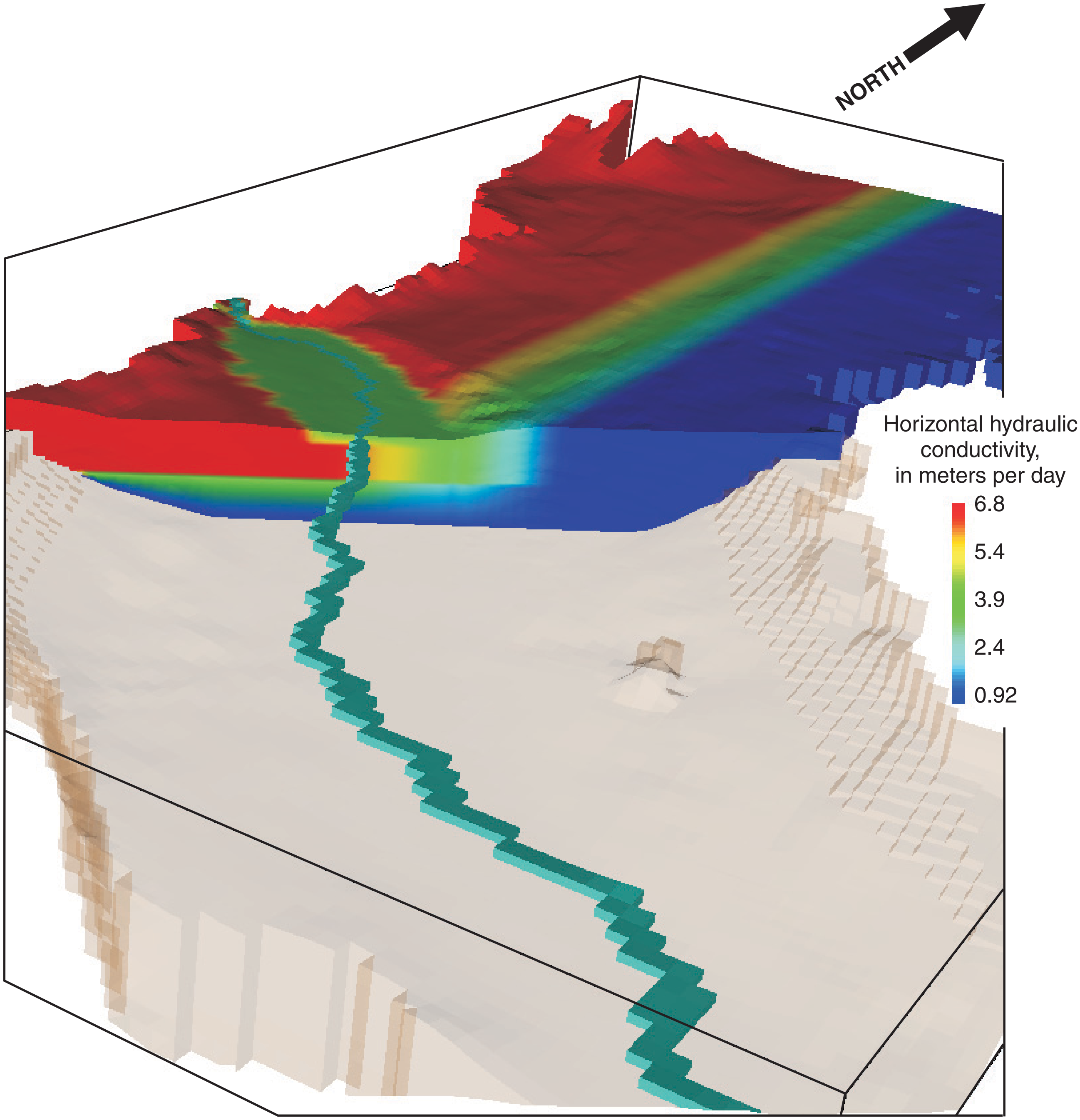


Figure 4. Cutaway perspective view showing generalized horizontal hydraulic conductivity of hydrogeologic facies (logarithmic color scale bar). Area of block is identical to that shown in figure 2.

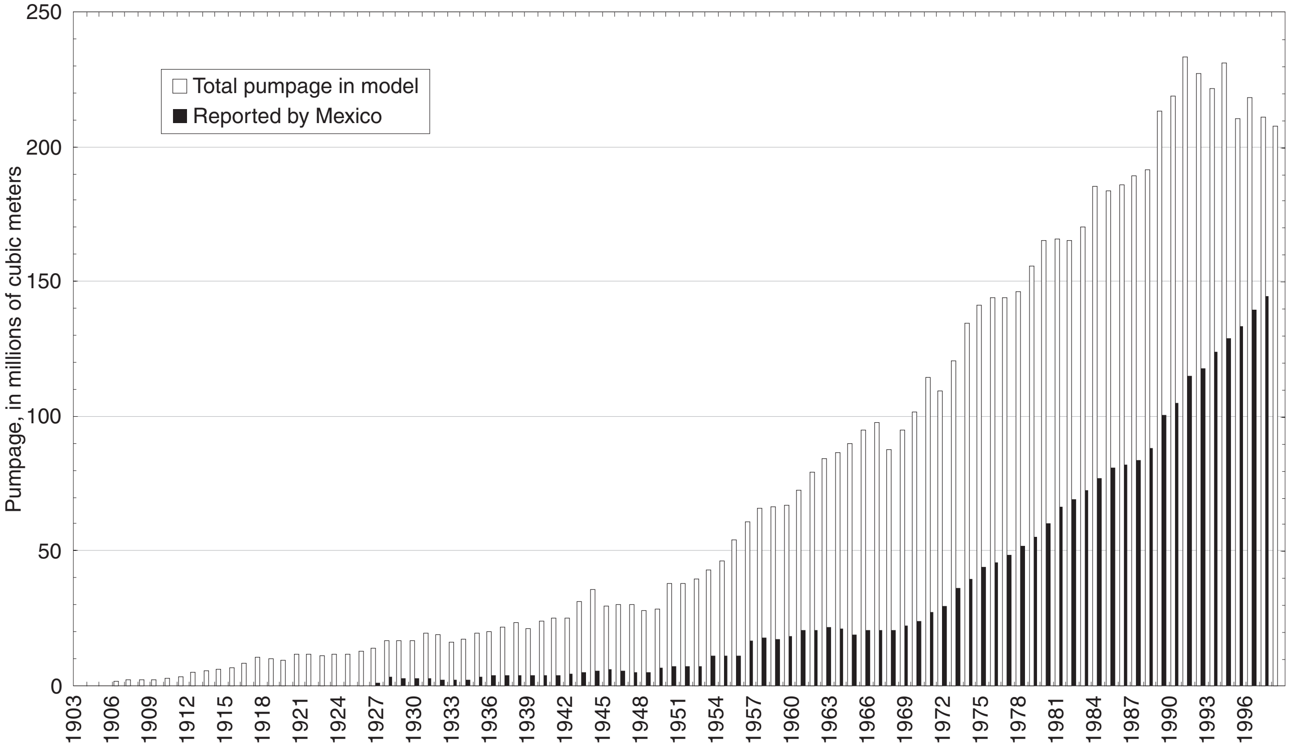


Figure 5. Ground-water withdrawals from the Hueco Bolson, 1903-96.

Rio Grande Valley Surface-Water System

The Rio Grande is hydraulically connected to the Hueco Bolson aquifer system. Locally, water from the river seeps into the shallow part of the aquifer system in the Rio Grande Valley. Much of this water may be transpired by agricultural crops and natural vegetation in the valley. Seepage from the Rio Grande between El Paso and Ciudad Juarez decreased substantially after December 1968, when flow was diverted into the concrete-lined American Canal upstream from the Chamizal zone.

The Chamizal (named after the desert shrub *Chamiza*) is a zone adjacent to the Rio Grande along the border between El Paso and Ciudad Juarez. Originally part of Mexico, the Chamizal became part of the United States when the border-defining Rio Grande changed course following a flood in 1864. In 1968, the Chamizal returned to Mexican ownership when the border was redefined along the newly constructed American Canal. At that time, the reach of the natural river channel south of the Chamizal was abandoned, and flow in the Rio Grande was diverted into the American Canal. The rate of ground-water-level decline near the American Canal accelerated following this diversion (Land and Armstrong, 1985), suggesting that decreased local aquifer recharge from the Rio Grande exacerbated these ground-water drawdowns.

The ACE, completed in 1999, conveys water that formerly flowed in a 15-km (9.3-mi) reach of the Rio Grande channel between the Chamizal zone and Riverside Dam (fig. 8). The canal was constructed, in part, to salvage water "lost" to seepage through the riverbed to the underlying shallow aquifer. This seepage was estimated for 1981 through 1983 by the International Boundary and Water Commission (IBWC) (Land and Armstrong, 1985; White and others, 1997). These seepage losses are summarized in table 1; the average loss for the 3 years was 1.03 x 10^5 m^3/d (83.3 acre-ft/d). The magnitude of this seepage varied as the hydraulic gradient changed between the Rio Grande and underlying aquifer. Ground-water levels generally declined under this reach through the 1980's and 1990's; thus, seepage from the Rio Grande probably increased during this period. The magnitude of this seepage (and by implication, the quantity of water "salvaged") is of interest to water management parties in the El Paso area.

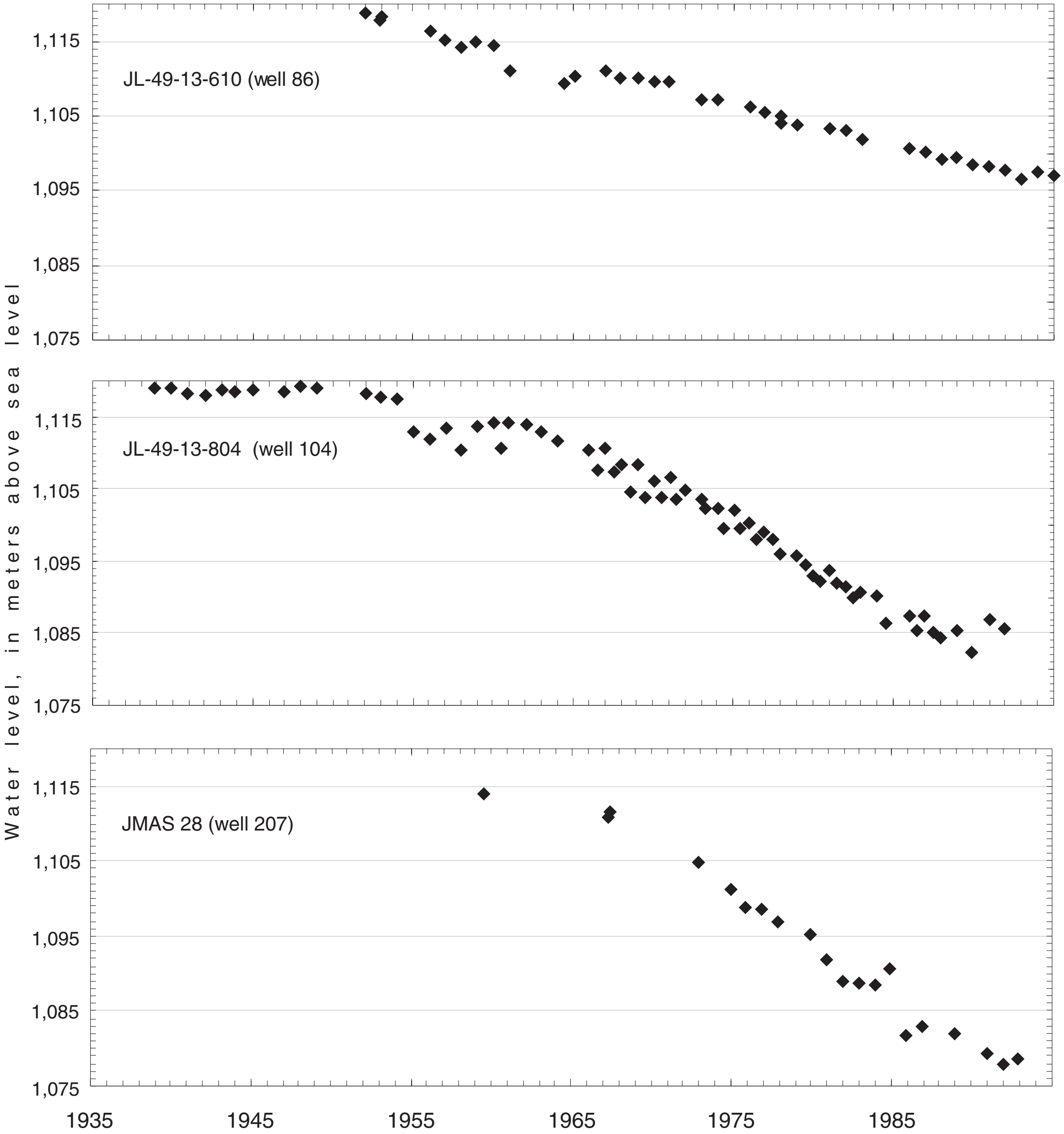


Figure 6. Water-level declines in selected wells in and near El Paso and Ciudad Juarez, 1935-96 (location of wells shown in figure 11).

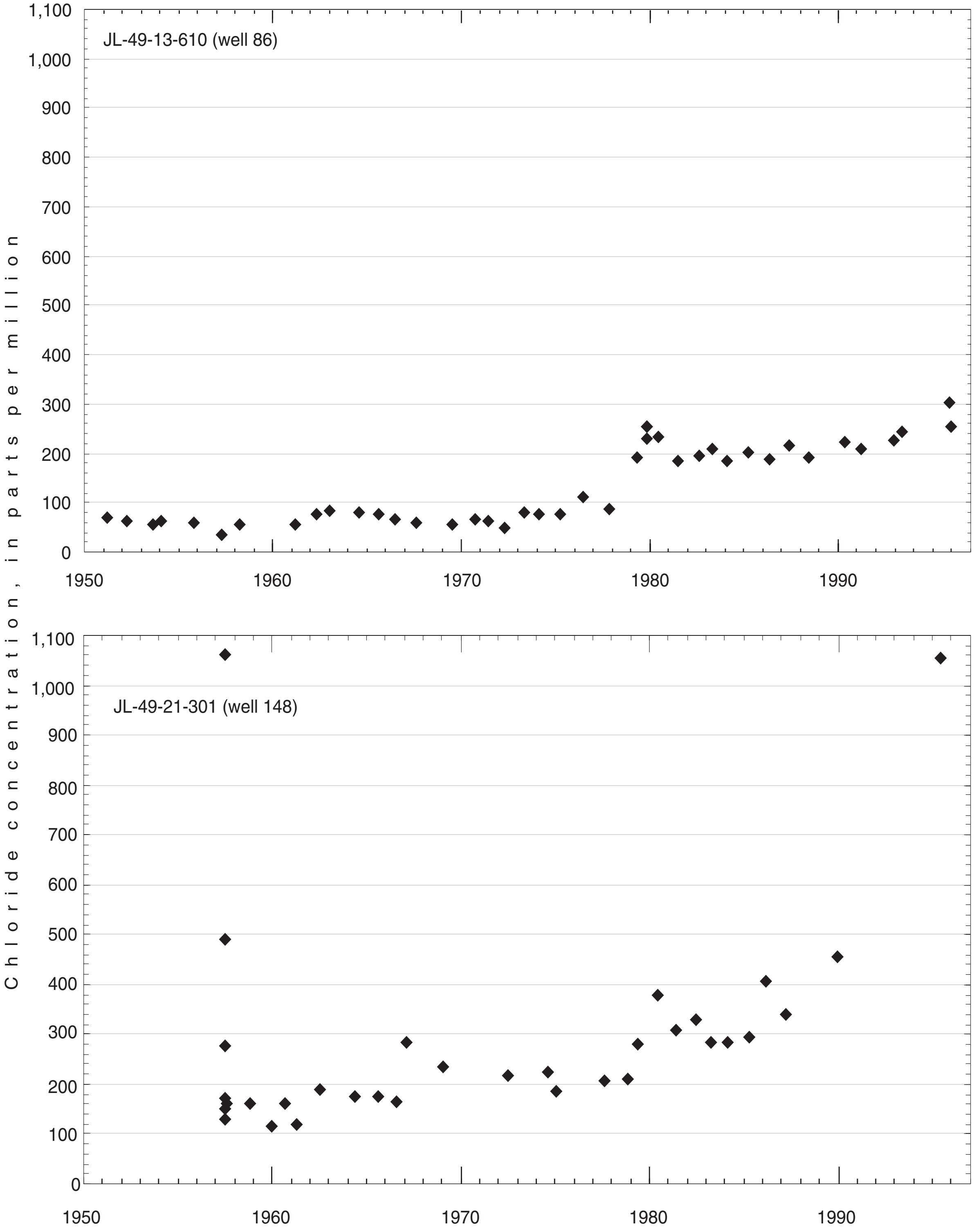


Figure 7. Increases in chloride concentration in selected wells, 1951-96 (location of wells shown in figure 11).

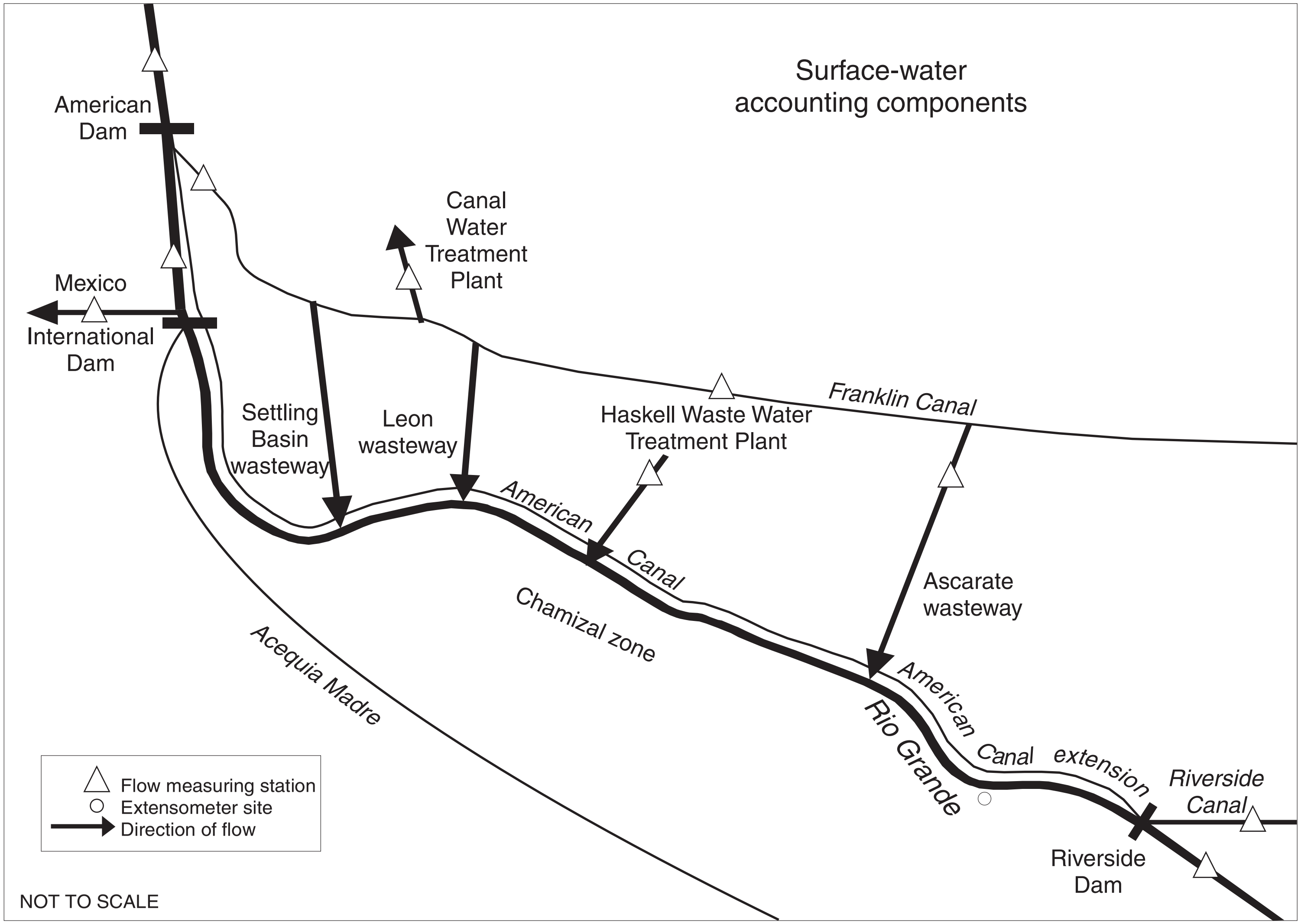


Figure 8. Schematic showing stream segments used for routing surface-water flows.

Table 1. Measured and simulated flow loss from unlined section of the Rio Grande above Riverside Dam and Franklin Canal

[IBWC, International Boundary and Water Commission; BOR, Bureau of Reclamation; USGS, U.S. Geological Survey; m^3/d, cubic meters per day]

Measurement	Measured flow loss	Simulated flow loss
Rio Grande 1981 (IBWC)	8.4×10^4 m^3/d	9.64×10^4 m^3/d
Rio Grande 1982 (IBWC)	1.06×10^5 m^3/d	9.82×10^4 m^3/d
Rio Grande 1983 (IBWC)	1.18×10^5 m^3/d	1.02×10^5 m^3/d
Franklin Canal 1984 (BOR)	1.05×10^4 m^3/d	9.81×10^3 m^3/d
Franklin Canal 1990 (USGS)	5.06×10^4 m^3/d	7.79×10^3 m^3/d
Franklin Canal 1991 (USGS)	5.42×10^4 m^3/d	1.23×10^4 m^3/d
Franklin Canal 1992 (USGS)	5.33×10^4 m^3/d	1.32×10^4 m^3/d

Agricultural Canals and Drains

Because the American Canal and its extension are concrete lined, they do not substantially interact with the shallow ground-water system. The Franklin Canal in the United States and the Acequia Madre in Mexico are major unlined irrigation-supply canals. These canals supply water through numerous subsidiary unlined irrigation canals to agricultural fields in the lower Rio Grande Valley.

To control shallow ground-water levels and prevent soil salinization, agricultural drains were installed in the Rio Grande Valley near El Paso beginning in the 1930's. These drains originally were designed and constructed with constant gradient; the Bureau of Reclamation (BOR) surveyed these drain-bed altitudes in the early 1960's. Since the 1960's, some drains have been destroyed by development, such as the construction of the ACE. From 1960 through 2000, the original gradient of many drains was not maintained (Al Blair, AWBlair Engineering, oral commun., June 2001). Infilling from windblown sand and lateral collapse increased drain-bed altitudes in segments of the lower valley drains. This may have decreased drainage efficiency, leading to the observed higher shallow ground-water levels and increased soil salinity in some lower valley agricultural fields.

Recharge

Precipitation over the Hueco Bolson is highly variable, both spatially and temporally. Mean annual precipitation over the Hueco Bolson is less than 25 cm (10 in.), most of which falls during the summer months. Sparse rainfall over the basin floor outside the Rio Grande Valley probably evaporates or transpires from the vadose zone before it can infiltrate to water-table depths and recharge the aquifer system. In the Rio Grande Valley, where the water table can be within several meters of land surface, precipitation or applied irrigation water has a better chance of infiltrating to the water table. Concentrated surface flows in arroyos below mountain canyons may infiltrate sufficiently to penetrate the vadose zone to the water table.

Ground-water age, defined as the time since water was in contact with the atmosphere, was estimated using carbon-14 age-dating techniques at eight different sites in the Hueco Bolson (Anderholm and Heywood, 2003). The calculated age of water in these samples ranges from 12,100 to 25,500 years old. The dates indicate that this water advected from recharge locations for some distance through the saturated zone.

Mountain-Front Recharge

By assuming that 25 percent of precipitation that falls in the catchments of the Organ and Franklin Mountains may bypass caliche layers at mountain fronts, Sayre and Livingston (1945) estimated that recharge to the bolson-fill aquifer from these areas may be as much as 50,000 m^3/d (15,000 acre-ft/yr). Meyer (1976) estimated total recharge from the Organ and Franklin Mountains, the Sierra Juarez, and underflow from the Tularosa Basin to be about 19,000 m^3/d (5,640 acre-ft/yr). Wilkins (1998) estimated recharge along the western boundary of the Tularosa-Hueco Basin to be about 245 $m^3/d/km$ (0.161 $ft^3/s/mi$). For the boundary length corresponding to the Organ and Franklin Mountains and Sierra Juarez in this study (approximately 80 km), this recharge estimate equates to about 19,600 m^3/d. Waltemeyer (2001) used the basin-climatic characteristics method to estimate streamflow available for potential recharge at the mouth of two canyons at the base of the Organ Mountains, which are in the area of this model. Total mean annual streamflow from the Oak and Soledad Canyon drainages was estimated to be 2,300 m^3/d;

some fraction of this flow may contribute to aquifer recharge.

Underflow from Tularosa and Mesilla Basins

Precipitation falling on the Sacramento and San Andres Mountains contributes to streamflow that infiltrates the basin alluvium shortly after flowing from mountain canyons onto the Tularosa Basin floor. Some of this infiltration water probably recharges the regional ground-water system. Ground-water levels in the Tularosa Basin (McLean, 1970) indicate that regional flow is to the south into the Hueco Bolson in Texas and to Lake Lucero, near White Sands Missile Range (fig. 1). Ground-water flow from the Tularosa Basin into the study area is probably a major component of recharge to the Hueco Bolson.

Ground-water underflow from the Mesilla Basin to the Hueco Bolson may occur adjacent to the Rio Grande through The Narrows. Slichter (1905) determined the alluvial thickness to be less than 26 m in this area and estimated underflow to be less than 270 m^3/d (80 acre-ft/yr).

Human-Induced Recharge

Land-use zoning maps indicate that agricultural acreage in the United States part of the Rio Grande Valley within the model area is approximately 227 km^2 (56,000 acres). About 1.2 m (4 ft) of irrigation water is applied to this acreage per year, of which 20 percent, or about 0.25 m (0.8 ft/yr), is estimated to infiltrate to the water table (Al Blair, oral commun., 2000). Much of this irrigation-return flow is intercepted by agricultural drains and returned to the Rio Grande.

Seepage from the Rio Grande is a major recharge component to the surrounding shallow aquifer system. Much of this water probably is subsequently discharged by evapotranspiration (ET) from the relatively shallow water table in the El Paso Valley.

From 1948 to 1952, EPWU tested injection of water into the Hueco Bolson aquifer system through a well in El Paso Valley (Roger Sperka, El Paso Water Utilities, oral commun., 1998). From 1971 through 1977, several valley wells were injected at a total average rate of about 700 m^3/d (200 acre-ft/yr). Beginning in 1981 and continuing through the 1990's, a major artificial recharge project north of El Paso injected 10 recharge wells at rates as high as 18,000 m^3/d (5,300 acre-ft/yr).

Discharge

Discharge from the deeper portions of the Hueco Bolson under valley and mesa areas is principally from ground-water pumping. Ground-water discharge mechanisms from recent alluvial deposits in the Rio Grande Valley are principally ET of infiltrated river water and applied irrigation water and seepage to agricultural drains and the Rio Grande.

Ground-Water Withdrawals

Records of historical pumpage from all known municipal supply, military, industrial, and private wells were compiled as part of this study. For wells in Mexico, annual pumpage summaries by well from 1926 through 1995 were obtained from the Junta Municipal de Agua y Sanimiento through the IBWC. Monthly summaries of pumpage by well for EPWU production wells and some military and industrial wells after 1967 were available.

Historical withdrawals from the Hueco Bolson, compiled from annual well pumpage records, are depicted in figure 5. Beginning in the 1950's, ground-water pumpage accelerated and reached a maximum of about 230 million m^3/yr (186,000 acre-ft/yr) by the late 1980's. The rapid growth of Ciudad Juarez since the 1970's is mirrored by increased ground-water withdrawals in Mexico. Ground-water pumping in the United States decreased during the 1990's as the City of El Paso began to use more treated water from the Rio Grande and ground water from the Mesilla Basin.

Evapotranspiration

The measured pan-evaporation rate from 1950 to 1980 at Ysleta Yard in El Paso was 4.9 mm/d (5.8 ft/yr) (Al Blair, written commun., 2000). Although measured pan evaporation is useful for estimating potential ET when the water table is near land surface, actual maximum ET rates may be higher or lower. Measured maximum ET rates for phreatophytes near the Pecos River in New Mexico (Weeks and others, 1987) and the Gila River in Arizona (Culler and others, 1982) ranged from 1 to 4 mm/d. Phreatophyte roots may extend to 9 m deep for cottonwood and greater for mesquite (Robinson, 1958).

Seepage to Rio Grande and Agricultural Drains

When shallow ground-water levels are higher than the water level in the adjacent Rio Grande, shallow ground water seeps into the Rio Grande where there is sufficient hydraulic conductance. Such ground-water inflow may occur southeast of El Paso, especially where shallow ground-water levels may be high from applied irrigation water and insufficient drainage from irrigated fields. The magnitude of seepage to agricultural drains can be estimated from flow measured in these drains. The BOR maintained records of this flow from 1960 through 1983 (Bureau of Reclamation, El Paso Field Division, written commun., 2000).

Land Subsidence

Elastic aquifer compression occurs when associated aquifer pore pressure is reduced by ground-water withdrawals and generally results in relatively small but measurable land subsidence. If ground-water levels decline in such a way that effective stresses in aquifer-system matrix materials exceed previous maximum magnitudes (the "preconsolidation stress level"), inelastic aquifer-system compaction may occur. For comparable incremental ground-water-level declines, inelastic aquifer-system compaction is typically one to two orders of magnitude greater than elastic compression and may result in substantial land subsidence (Riley, 1998).

First-order, first-class geodetic level lines were surveyed by the National Geodetic Survey in the Hueco Bolson in 1953, 1981, and 1993. By assuming stable benchmark points on bedrock in the Hueco and Franklin Mountains, the relative change in benchmark altitudes was determined for points in the Hueco Bolson for 1953-81 and 1981-93. As of 1993, the maximum measured altitude change at a benchmark near downtown El Paso was 0.25 m (0.82 ft) (Emery Balasz, National Geodetic Survey, written commun., 1994). This magnitude of altitude change is consistent with elastic compression of the aquifer matrix resulting from measured ground-water drawdowns. Evidence that preconsolidation levels have been exceeded has not been documented in the Hueco Bolson.

STEADY-STATE AND TRANSIENT GROUND-WATER FLOW MODEL

Because brackish to saline ground water is present in the Hueco Bolson, the significance of density-driven flow effects was evaluated before the numerical code to be used for model development was selected. For this purpose, the Groschen (1994) model was used for preliminary flow-system analysis. Running several density-dependent simulations using HST3D tested the magnitude of density-driven ground-water flow from heterogeneous solute concentrations. These profile models were run with identical boundary conditions and hydraulic properties using alternate assumptions of homogeneous or heterogeneous ground-water density. For the brackish to moderately saline conditions present in the Hueco aquifer system, computed differences between the homogeneous and heterogeneous density assumptions were noticeable for only a test case of isotropic hydraulic conductivity. For horizontal to vertical hydraulic-conductivity ratios greater than 10:1 to 100:1, which are probable for Hueco Bolson deposits, density-driven flow effects are negligible. For the purposes of this study, the assumption of constant ground-water density was concluded to be an appropriate approximation of the physics of ground-water flow.

Because of the large size of this ground-water flow simulation and the need for effective model calibration, three versions of the numerical model of the Hueco Bolson were constructed:

(1) A MODFLOW model with 1 steady-state and 96 annual transient stress periods,

(2) A MODFLOWP model with 96 annual stress periods, and

(3) A MODFLOW model with 66 annual and 408 monthly stress periods.

The MODFLOW model (version 1) was first constructed to build a reasonable simulation of the Hueco Bolson. An equivalent MODFLOWP model (version 2) was subsequently constructed to enable model calibration by the inverse method (Hill, 1992). These two versions were frequently run with equivalent parameter definitions and distributions to ensure model equivalency and to provide error checking. After an optimal parameter set had been determined with MODFLOWP and translated to an equivalent MODFLOW input, a MODFLOW (version 3) simulation with refined monthly discretization was run. The monthly MODFLOW simulation was checked for general equivalency to the results of the annual MODFLOW and MODFLOWP simulations. The minor differences in hydraulic heads and budgets are attributable to the difference in temporal discretization.

Numerical Method

Both MODFLOW and MODFLOWP use the finite-difference method to solve a form of the ground-water flow equation:

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right]-W=\frac{\partial h}{\partial t}S_s \quad (1)$$

where

K_{xx}, K_{yy}, and K_{zz} = principal components of the hydraulic-conductivity tensor;
h = hydraulic head;
W = source/sink;
t = time; and
S_s = specific storage.

Pumping from the Hueco Bolson aquifer since 1903 has lowered water levels by more than 50 m (197 ft) in some areas of El Paso and Juarez, dewatering part of the modeled area that corresponds to the top two model layers. This situation is represented in MODFLOW by removal of dewatered (dry) cells from the simulation and conversion of the underlying cells from confined to unconfined conditions by increasing the value of the storage coefficient. Simulation of dewatering in the upper part of the Hueco Bolson aquifer required changes to MODFLOWP and MODFLOW, however. Both codes were further modified by incorporating the multi-aquifer well package (MAW) (McDonald, 1984), which computes flow to pumped wells screened in more than one model layer. These modifications are detailed in the appendixes and summarized in the next two subsections.

Aquifer Dewatering

MODFLOWP allows spatial and temporal interpolation in the computation of hydraulic head at specific locations in the modeled area and also computes mean head in observation wells screened in more than one model layer. However, the interpolation procedure used to compute heads in these multilayer observation wells does not support the dewatering condition described in the previous section. The interpolation procedure defined by Hill (1992) was modified by omitting dry layers screened by a multilayer observation well and using only the remaining saturated layers in the computation of head in the well (h_w) (fig. 9A).

Neither MODFLOWP nor MODFLOW simulates stream leakage in model cells that are dry, although the actual stream channels represented in the model continue to leak at a constant rate as the water table declines. The stream package (Prudic, 1989) was modified in both codes to allow continuing stream leakage to the aquifer following the procedure used in the recharge package, in which areally distributed recharge enters the topmost active cell if the upper layers in the model are dry (fig. 9B). This modification also required changes to the computation of stream leakage reported in both the water budget and flow observations computed by MODFLOWP.

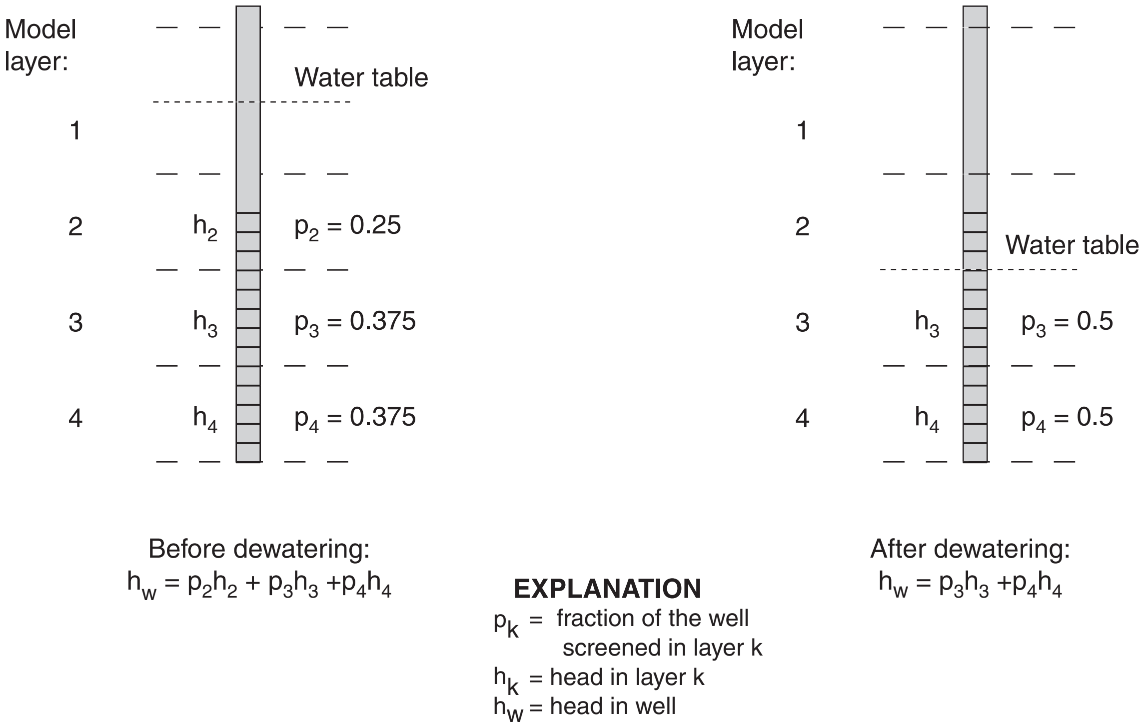
Multi-Aquifer Wells

The screened intervals of pumped wells in the Hueco Bolson average more than 100 m; most of these wells are screened in more than one model layer. The MAW package (McDonald, 1984) was used to compute discharge from each model layer (q_k) to a well using the total discharge (Q_w) specified for the well. The method used in the MAW package was described by Bennett and others (1982) and has been previously applied in ground-water flow models developed by Kontis and Mandle (1988) and by Groschen (1994). The method is based on the Thiem (1906) equation describing steady-state radial flow to a discharging well:

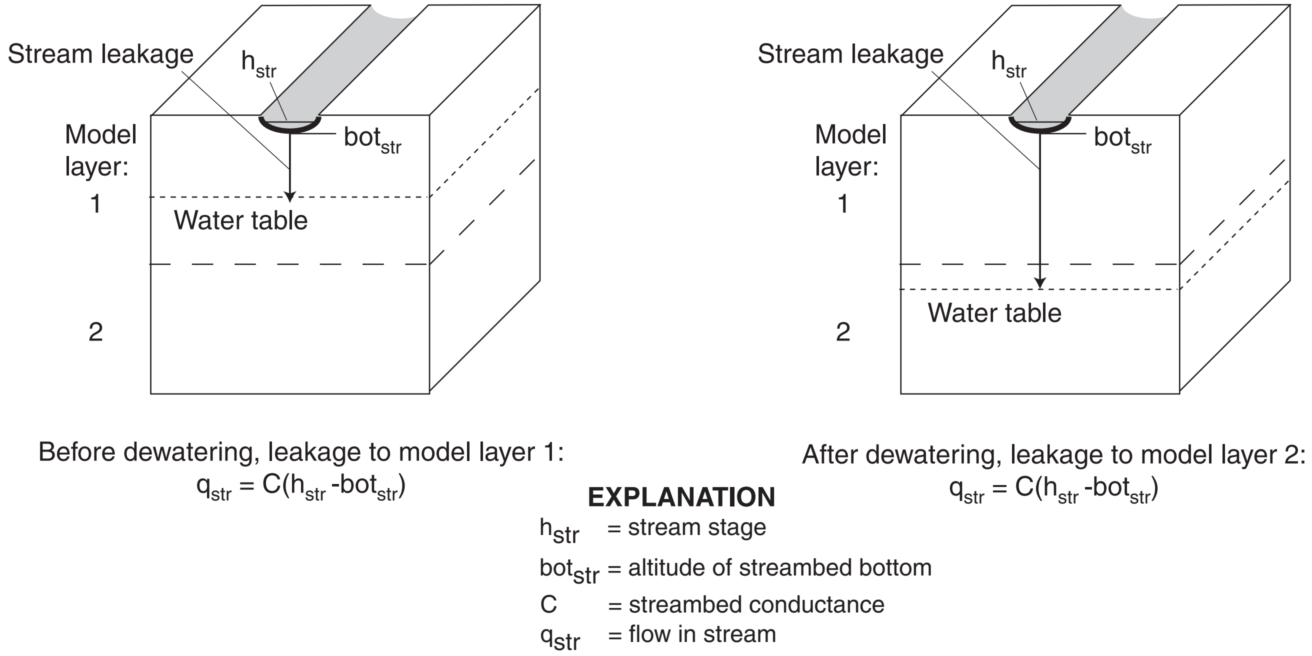
$$h-h_w=\frac{Q_w}{2\pi T}\ln\left(\frac{r}{r_w}\right) \quad (2)$$

where h = hydraulic head at a distance r from the well [L];
h_w = hydraulic head at the well radius r_w [L];
Q_w = well discharge [L^3T]; and
T = transmissivity [L^2T].

Prickett and Lonnquist (1971) and Trescott and Larson (1976) used the Theim equation in a finite-difference ground-water flow model to estimate h_w in a discharging well from the head computed at a cell representing the well. In their applications, h was assumed to be equivalent to the head at an effective radial distance (r_a) from a well located at the center of



(A) Computation of head in partially dewatered, multilayer observation wells.



(B) Stream leakage through dewatered model cell.

Figure 9. Modifications to MODFLOWP and MODFLOW.

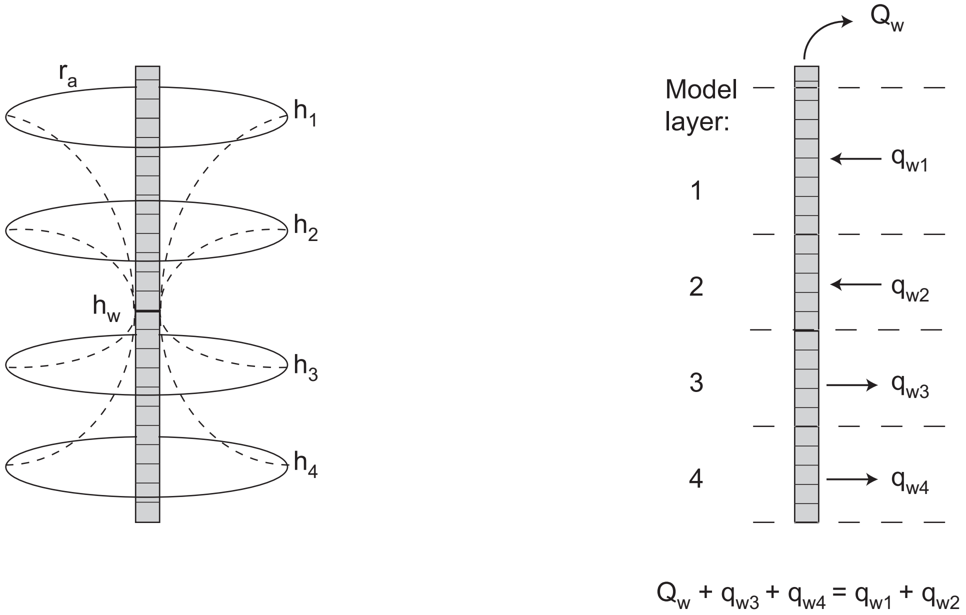
a square cell with length (Δx) (fig. 9C). Bennett and others (1982) approximated the effective radius as:

$$r_a = \frac{\Delta x}{4.81} \qquad (3)$$

and showed that h_w in a multi-aquifer well at cell ij screened in model layers m to n can be computed from:

$$h_w = \frac{\sum_{k=m}^{n} \frac{T_{ijk} h_{ijk}}{\ln(r_{ak}/r_w)}}{\sum_{k=m}^{n} \frac{T_{ijk}}{\ln(r_{ak}/r_w)}} - \frac{Q_w}{2\pi \sum_{k=m}^{n} \frac{T_{ijk}}{\ln(r_{ak}/r_w)}} \qquad (4)$$

where the subscripts = row i, column j, and layer k and Q_w = the algebraic sum of discharges to the well from layers m through n. Discharge to the well from each model layer (q_{wk}) can then be computed from the Theim equation (eq. 2) by substituting values for h_w and h_{ijk}. McDonald (1984) incorporated this method in the MAW package that was written for use with MODFLOW. The MAW package was modified for this study to support dewatering of model layers by omitting dry layers from the computation of h_w in equation 4 and apportioning flows q_{wk} to or from the well in the remaining saturated layers.



EXPLANATION

q_{wk} = flow to or from the well in layer k
r_a = effective well radius
Q_w = well pumpage

(C) Distribution of hydraulic head and flow near multilayer pumped well.

Figure 9. Modifications to MODFLOWP and MODFLOW: (figure 9C modified from Bennett and others, 1982)--Concluded.

The assumption of radial flow to a single well located in the center of a model cell limits the accuracy of the method's representation of certain conditions. The assumption of radial flow is not strictly satisfied at model cells adjacent to an impermeable boundary, so wells in these cells are not represented in the MAW package. Kuniansky and Hillestad (1980) showed, however, that if a well is located in the center of a cell adjacent to an impermeable boundary, the error in h_w using the r_a value computed with equation 3 is less than 5 percent of the exact value computed with an analytical solution.

Another potential problem is representing closely spaced, multilayer wells with combined pumpage that produces an actual head (h_w) lower than the value computed by the MAW package. The combined drawdown produced by closely spaced wells could be computed by the use of smaller model cells to more accurately represent each well or superposition (Reilly and others, 1984) by combining the discharge or recharge from multiple wells into a single well within the model cell. The head (h) computed for a model cell in several test cases was determined to be relatively insensitive to the choice of these alternative methods, however, so multi-aquifer wells were specified individually in this model.

Spatial Discretization

To analyze pumping effects of individual wells, the finite-difference model grid was designed to maximize spatial detail yet retain reasonable execution time. Unconsolidated deposits ranging from 138 to 693 m thick above an altitude of 600 m are represented with 10 model layers. Each model layer consists of 165 rows and 100 columns of cells 500 or 1,000 m on either side. Model layer 1 contains 10,895 active cells and represents a larger area (5,099 km^2) than deeper model layers because the basin narrows with depth (fig. 3); layer 10 (the bottom layer) contains 8,809 active cells and represents an area of 3,839 km^2. To maintain an approximately constant depth below land surface, the model-grid altitudes of all model layers increase to the north with a gradient of 1:1,000 to the approximate location of the Texas-New Mexico State line, north of which the layers are horizontal.

Recent alluvial deposits in the Rio Grande Valley are represented in model layer 1, which has an average thickness of 30 m (fig. 3). Along the western margin of the basin, the fluvial facies is represented in model layers 1 through 9, each of which is 30 m thick. The lacustrine-playa facies is represented along the eastern margin of the basin in model layers 1 through 9 and throughout the model in layer 10, which varies in thickness from 0 to 276 m.

Vertical Datums

The El Paso area has six different vertical datums, three of which were encountered in data used to define altitudes of various model boundaries. Measured hydraulic heads were referenced to the National Geodetic Vertical Datum of 1929 (NGVD-29), which was also used as the vertical datum for this study. Altitudes of the Rio Grande channel surveyed by the IBWC were referenced to the IBWC datum; these were converted to NGVD-29 by adding 0.348 m before streambed altitudes in the model were defined. Altitudes of agricultural drains surveyed by the BOR were referenced to an old datum of the Santa Fe Railway; these were converted to NGVD-29 by adding 12.891 m before drain-bed altitudes in the model were defined. The differences among vertical datums used to perform these conversions are listed in table 2.

Table 2. Conversions between vertical datums in the El Paso, Texas, area

Datum	Santa Fe Railway	International Boundary and Water Commission (IBWC)	National Geodetic Vertical Datum of 1929 (NGVD-29)
Santa Fe Railway	0	+ 12.543 meters	+ 12.891 meters
IBWC	- 12.543 meters	0	+ 0.348 meter
NGVD-29	-12.891 meters	-0.348 meter	0

Temporal Discretization

A steady-state simulation was used to represent predevelopment conditions and to obtain starting heads for the transient simulation. Sixty-six annual stress periods and time steps were used to simulate 1903 through 1968. Because the model parameter-estimation process required thousands of model runs, using monthly stress periods during the model-calibration process was not possible. A MODFLOWP simulation with steady-state and 93 annual stress periods was constructed to simulate the time period of calibration data, which extended through 1995. The optimal parameter set obtained with MODFLOWP was used to generate an annual stress-period MODFLOW data set so that both models could be run and checked for equivalency. The 1968 head distribution from the annual stress-period MODFLOW simulation was used as a starting head distribution for the monthly stress-period simulation, which represented 1969 through 2002.

Seasonal variations in Rio Grande flow, ground-water pumping, irrigation recharge, and ET cause hydraulic-head variations that cannot be represented with annual stress periods. To accurately incorporate these seasonal effects, a MODFLOW simulation (version 3) was discretized with 408 monthly stress periods from January 1969 through December 2002. This simulation was identical to the annual MODFLOW (version 1) and MODFLOWP simulations (version 2) for the first 66 annual stress periods, which simulate 1903-68. Parameter values and distributions, as well as annual total pumpage stresses, were identical to those in the annual simulations. Monthly temporal discretization enabled more accurate calculations of Rio Grande seepage losses along the 15-km (9.3-mi) reach between the end of the lined section of the Chamizal zone and Riverside Dam.

Boundary Conditions

Specified-flow boundaries represent recharge along the basin margins and beneath irrigated fields and discharge from pumped wells screened in the fluvial facies (figs. 3 and 4). Head-dependent boundaries represent seepage losses from stream channels, including the Rio Grande and several irrigation canals, and ground-water discharge to stream channels, agricultural drains, and ET.

Specified-Flow Boundaries

Specified-flow boundaries in model layer 1 represent infiltration from ephemeral streams draining the mountains that border the Hueco Bolson and leakage from irrigation-return flows. In model layers 1 through 9, specified-flow boundaries represent underflow from upgradient areas in the Tularosa and Mesilla Basins. Rates of recharge and underflow were included in the estimated parameter set considered in the nonlinear regression. Mountain-front recharge is applied along arroyo channels on the east side of the basin and at the base of the Organ and Franklin Mountains in the United States and a 14-km^2 (5.4-mi^2) area at the base of the Sierra Juarez in Mexico. The estimate of mountain-front recharge (800 m^3/d) is smaller than values used in previous modeling studies in the area (Meyer, 1976; Groschen, 1994). During simulation stress periods after 1924, recharge also is applied to model cells that represent irrigated fields in the United States and Mexico. The maximum recharge rate represents the volume of water typically applied in excess of crop requirements in the United States (Al Blair, oral commun., 2000). During drought and low-flow years, this rate was scaled so that applied irrigation water would not exceed the total surface water available. The types and acreage of irrigated crops have changed during the past 100 years, but little information is available to document these changes over the entire simulation period, particularly in Mexico. The irrigated area (approximately 180 km^2) and maximum rate of return flow are, therefore, considered constant in the model simulation.

Specified flows represent underflow from the Tularosa Basin along the northern model boundary and from the Mesilla Basin (Slichter, 1905). Ground-water withdrawals through pumped wells are specified in model layers 1 through 9 using 1903-96 annual pumpage rates in 424 wells. Thirty-two wells that are screened within only one model layer are represented with the MODFLOW well package, and the remaining 392 wells are represented with the MAW package described earlier. About 60 percent of the wells are located in the United States, including 10 wells that are used to recharge water to the bolson aquifer.

Head-Dependent Flow Boundaries

The exchange of water between stream channels and recent alluvial sediment in the Rio Grande Valley is simulated with the stream package in MODFLOW. Ground-water discharge to agricultural drains is simulated with the drain package. In both packages the flow of water between the boundary and the underlying model cell is a function of the head in the stream or drain, the head in the model cell, and the hydraulic conductance of the sediment in the channel bed:

$$C = \frac{kA}{b} \qquad (5)$$

where k = vertical hydraulic conductivity of the bed sediment $[LT^{-1}]$;

A = area of the streambed or drain bed in the cell $[L^2]$; and

b = thickness of the bed sediment [L].

Geographic information system (GIS) coverages of the Rio Grande, canals, and drain channels enabled accurate calculation of the length of these features within each model cell. Surveyed widths of the Rio Grande between the Chamizal zone and Riverside Dam (Dr. Rong Kuo, U.S. International Boundary and Water Commission, written commun., 1999) were used to calculate the streambed area *(A)* of the Rio Grande channel for corresponding model cells. The average of these widths (30 m) was used to calculate streambed area for reaches where surveyed widths were unavailable. The portion of agricultural drains through which water seeps (wetted perimeter) is variable but was estimated during field reconnaissance to average about 3 m. Altitudes of drain-bed end points surveyed by the BOR in 1960 were assigned to the associated drain in a GIS coverage. Altitudes of intermediate points along each individual drain were determined by linear interpolation along the arc length between the end points. The drain-bed altitude assigned to each flow-model cell was the average altitude of all drains within that cell. The reasonability of these altitudes was verified by comparing them with cell-average values derived from digital elevation models (DEM's), corrected for an assumed drain-bed depth of 2-3 m. Because drains may have filled in with sediment since 1960, drain-bed altitudes in some model runs were increased by 1 m during the calibration process.

Channel-bed thickness of the Rio Grande, canals, and drains was assumed to be about 1 m. Because the bed thickness is somewhat uncertain and wetted perimeter widths vary, the vertical conductance per unit length of each of these features, rather than the vertical hydraulic conductivity, was included in the estimated parameter set considered in the nonlinear regression.

In the ground-water flow simulations, essentially nonirrigated and undrained agricultural conditions change to irrigated and drained conditions in the Rio Grande Valley in 1925. (For ground-water seepage to the 21 major agricultural drains simulated with the drain package in MODFLOW and MODFLOWP, the reader is referred to figure 18D.)

ET from nonirrigated riparian land in the Rio Grande Valley was represented using the ET package of MODFLOW and MODFLOWP. Land-surface altitudes throughout the model were obtained from 28-m DEM's. Maximum depths of ET between 2.5 and 9 m were tested during model calibration. Although the model was not particularly sensitive to ET extinction depth, the best model fit had an ET extinction depth of 5 m. The initial estimate (4 mm/d) of the maximum ET rate was refined through the regression process to a final value of 4.6 mm/d.

Streamflow Routing

As calculated with the stream package in MODFLOW, water seepage between the Rio Grande and the underlying aquifer is dependent on (1) the difference in hydraulic head between the boundary reach representing the Rio Grande and the model cell representing the underlying aquifer and (2) the hydraulic conductance between the two.

Boundary heads representing water levels of the Rio Grande, Franklin Canal, Ascarate wasteway, and Acequia Madre are computed with the Manning equation in the stream package (Prudic, 1989). Streambed slope, width, and roughness are spatially variable properties specified for each boundary reach. Stream discharge, or flow in a particular boundary reach, varies both spatially and temporally. The slope of each stream reach was computed from surveyed altitudes, if available, or interpolated from digital elevation data. Manning's n was specified as 0.03 for the Rio Grande channel and 0.004 for the Franklin Canal, Ascarate wasteway, and Acequia Madre. The time-varying flow in the first reach of stream segments representing the Rio Grande, Franklin Canal, Ascarate wasteway, and Acequia Madre was specified in the stream package in MODFLOW. The stream stage in each of these starting stream reaches was computed from this flow using the Manning equation. Discharge into each subsequent downstream stream reach was adjusted by seepage loss or gain from the connected aquifer model cell, and stream stage in each reach was calculated with the Manning equation.

Surface-water flows in the Rio Grande, American Canal, Franklin Canal, Ascarate wasteway, and Acequia Madre in Mexico were simulated with seven stream segments in the stream package (fig. 8). Diversions from the Rio Grande flow into the Franklin Canal and Acequia Madre. A diversion from the Franklin Canal back to the Rio Grande flows in the Ascarate wasteway. Flow in the Franklin Canal is routed back to the Rio Grande through the Tornillo Canal.

Daily records of flow in the Rio Grande at American Dam, diversion into the Franklin Canal, and diversion to Mexico at International Dam from June 1, 1938, through December 31, 1996, obtained from the IBWC (2000) were used to compute mean annual and mean monthly input flow specifications for stream segments representing the Rio Grande, American Canal, Franklin Canal, and Acequia Madre. Water diverted from the Franklin Canal back to the Rio Grande was specified according to measurements obtained from the BOR (El Paso Field Division, written commun., 2000).

Mean annual flows in the Acequia Madre, Franklin Canal, and Rio Grande from 1903 through 1996 are shown in figure 10A. Diversions from the Rio Grande into the Franklin Canal began in 1938. Flow in the Rio Grande was virtually nonexistent during the drought years of 1954-57. The late 1970's were relatively dry years; flow during this period is shown in monthly detail in figure 10B. In contrast, the late 1980's to early 1990's were relatively wet; flow during this period is shown in monthly detail in figure 10C.

Flow in the stream segment simulating the Rio Grande at the end of the Chamizal zone was specified for the monthly stress periods beginning in January 1969. Because Rio Grande flow was measured upstream from the lined section of the American Canal, the flow specified for the simulation required adjustment to account for tributary inflow and loss between the streamflow-gaging station and the start of the unlined section of the Rio Grande. These adjustments were made according to an analysis of the El Paso County Water Improvement District canal system (Al Blair, written commun., January 26, 2000). Additions to the flow measured downstream from American Dam were made to account for inflow from the Settling Basin wasteway, Leon wasteway, and Haskell Waste Water Treatment Plant. The accumulated flow was debited to account for the diversion to Mexico at International Dam and estimated evaporation in the canal between American Dam and the downstream end of the Chamizal zone. This flow is summarized in equation form:

$$Q_{seg} = Q_{amer} - Q_{mex} + Q_{sb} + Q_{leon} + Q_{hask} - Q_{evap} \tag{6}$$

where Q_{seg} = specified inflow to the stream segment below the Chamizal zone;

Q_{amer} = measured flow in the American Canal below American Dam;

Q_{mex} = measured diversion to Mexico at International Dam;

Q_{sb} = flow in the Settling Basin wasteway;

Q_{leon} = flow in the Leon wasteway;

Q_{hask} = return flow from the Haskell Waste Water Treatment Plant; and

Q_{evap} = estimated total evaporation from the American Canal between American Dam and the end of the Chamizal zone.

Because tributary inflows from the Settling Basin wasteway and Leon wasteway were not directly measured, their inflow was derived by subtracting the measured flow in Franklin Canal and the diversion to the Canal Water Treatment Plant from the measured flow in Franklin Canal downstream from American Dam. In equation form:

$$Q_{sb} + Q_{leon} = Q_{frank1} - Q_{wtp} - Q_{frank2} \tag{7}$$

where Q_{frank1} = measured flow in the Franklin Canal below American Dam;

Q_{wtp} = measured diversion to the Canal Water Treatment Plant; and

Q_{frank2} = measured flow in the Franklin Canal between the Leon and Ascarate wasteways.

Monthly return flows from the Haskell Waste Water Treatment Plant (Q_{hask}) were relatively constant (Roger Sperka, oral commun., June 2000), enabling use of a constant average flow of 75,708 m^3/d. The monthly evaporative fluxes (Q_{evap}) were generated from local pan-evaporation rates by Al Blair (written commun., 2000).

To specify monthly flow in the Rio Grande from 1994 through 2004, a "design flow" was synthesized from other components of the El Paso surface-water budget (Al Blair, written commun., 2000). The specified flow for the stream-package segment representing the Rio Grande downstream from the Chamizal zone was set equal to 60 percent of the design diversion to El Paso plus the design diversion at Riverside plus the computed seepage loss in the 15-km reach between the Chamizal zone and Riverside Dam. (Because the seepage loss in this segment was computed with the ground-water flow model, which required this flow specification as input, several iterations of the model were run to obtain a flow specification.) This calculation may be summarized as:

$$RioGrande = 0.6(diversion) + seepage + Riverside \tag{8}$$

The resulting design-flow specifications for stream segments representing the Acequia Madre, Franklin Canal, and Rio Grande are shown in figure 10D.

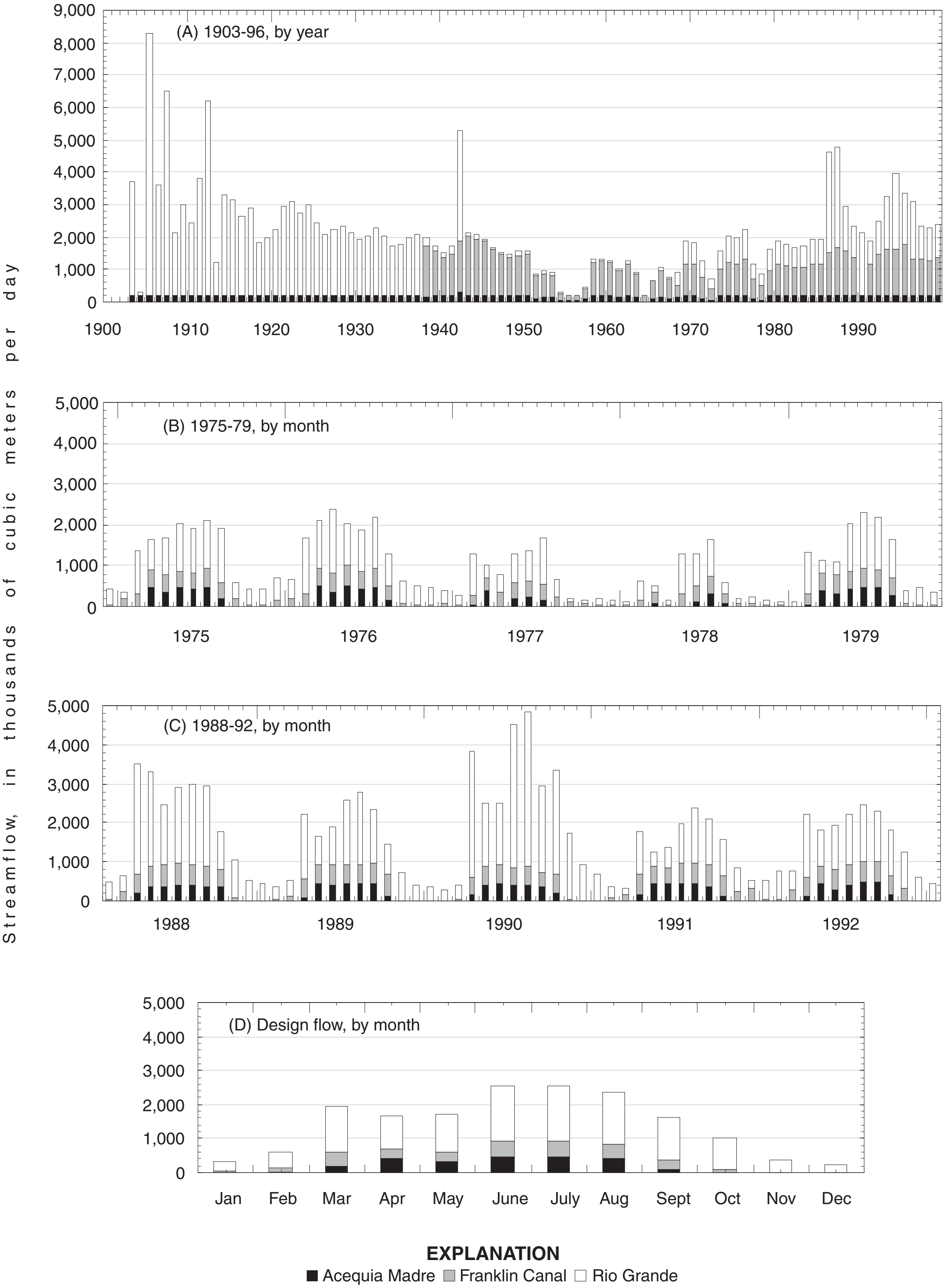


Figure 10. Mean annual and mean monthly flows in Rio Grande and diversions, 1903-96.

Faults

Fault gouge in subvertically dipping fault planes may impede horizontal fluid flow and affect ground-water flow patterns (Haneberg and others, 1999). Several intrabasin faults deforming Quaternary alluvium are recognized northeast of El Paso (Barnes, 1983) (fig. 11). To evaluate the influence of these faults on ground-water flow, they were incorporated into the ground-water flow simulation with the Horizontal Flow Barrier package (Hsieh, 1992).

Storage Properties

Water in storage in the aquifer system may be released by three main processes: (1) drainage of pore space in unconfined layers, (2) expansion of water, and (3) compression of the aquifer matrix. Drainage of water from pore space above a declining water table is the dominant process yielding water to the ground-water flow system and is quantified by specific yield (S_y). Specific yield generally ranges from 10 to 20 percent. Its magnitude in the Hueco Bolson was estimated in the model-calibration process as a uniform value throughout the alluvial deposits. Specific yield and the component of specific storage that is due to the expansion of water (which is very minor) were simulated with the Block-Centered-Flow package in MODFLOW and MODFLOWP. The skeletal components of specific storage, which quantify water derived from compression of the aquifer-system matrix, were simulated with the Interbed-Storage package in MODFLOW and MODFLOWP. The magnitude of elastic skeletal specific storage (S_{ske}) is reasonably well constrained by plausible physical properties of alluvial deposits. In the El Paso area, onsite estimates of S_{ske} (Heywood, 1995) have been made from piezometric-extensometric measurements; this value ($S_{ske} = 7 \times 10^{-6}\ m^{-1}$) was specified in the flow model.

MODEL CALIBRATION

MODFLOWP computes the changing spatial distribution of ground-water heads and fluxes across head-dependent boundaries, which were used to represent the Rio Grande, irrigation canals, and agricultural drains. During model calibration, parameter values were adjusted to minimize differences between computed and measured heads and fluxes. A total of 4,439 measurements of heads and flow losses or gains compose the calibration data set (fig. 12).

Hydraulic-Head Measurements

The nonlinear regression included 4,352 heads measured between 1912 and 1995 in 310 wells. These measurements were compiled from databases of EPWU and the U.S. Geological Survey (USGS). About 83 percent (3,615) of the measurements were made in 226 wells in the United States, and the remainder (737) were made in 84 wells in Mexico. Most of the heads have been measured since ground-water withdrawals increased significantly in the 1960's (fig. 12). Of the total set of measurements, 4,184 were made in wells with screened intervals corresponding to more than one model layer; these were defined as multilayer head measurements in MODFLOWP.

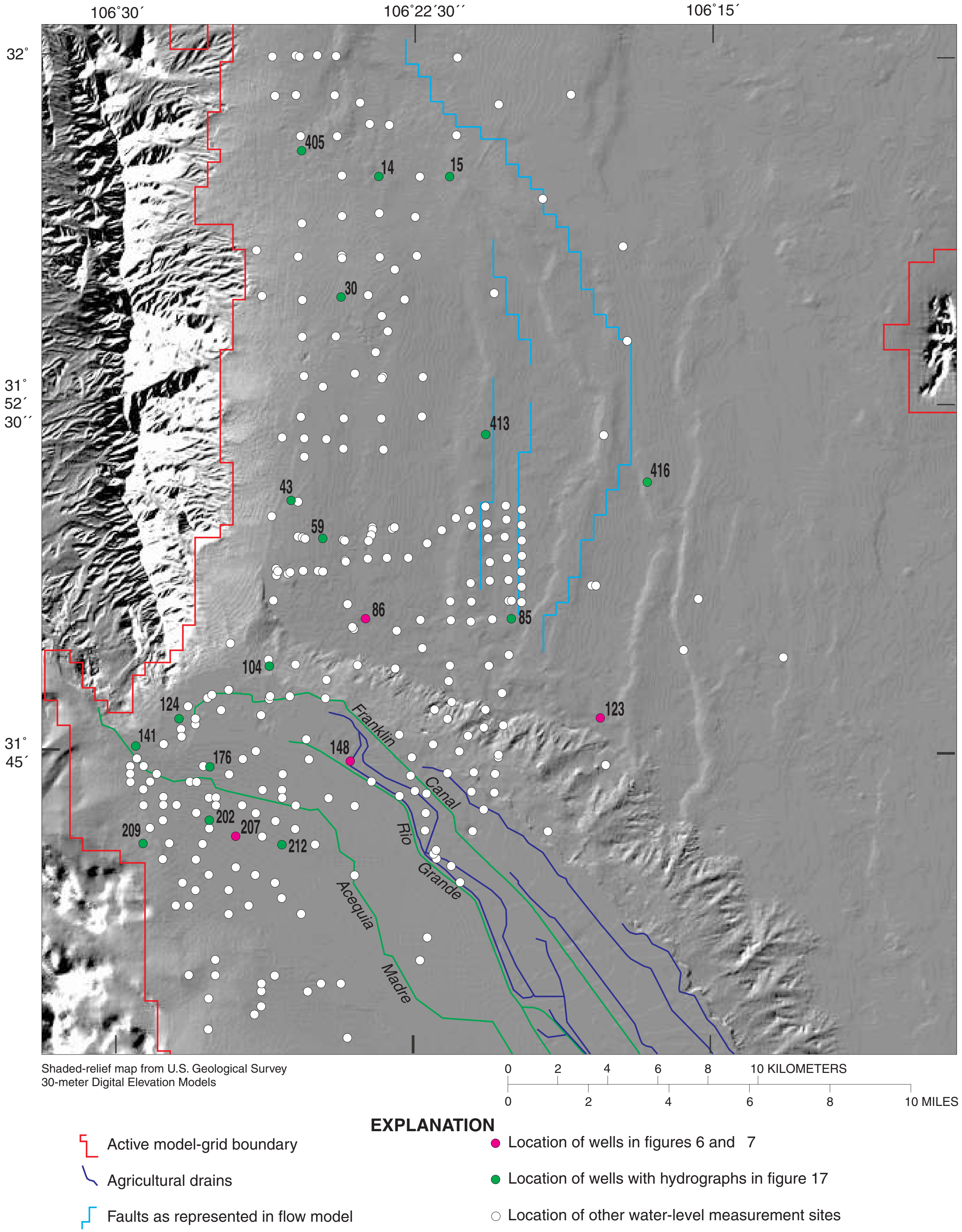
Flow Measurements

Measurements of streamflow loss in the Rio Grande and Franklin Canal and seepage into the Island Drain were used to constrain the nonlinear regression. The IBWC computed seepage loss from the Rio Grande into the underlying aquifer along a 15-km (9.3-mi) reach between the concrete-lined section in the Chamizal zone and Riverside Dam for 1981, 1982, and 1983 (Land and Armstrong, 1985; White and others, 1997). The BOR computed flow loss along an 8.5-km (5.25-mi) reach of the Franklin Canal for 1984, and the USGS computed flow loss for 1990 through 1992 (Land and Armstrong, 1985; White and others, 1997). These computations and simulated flow losses are summarized in table 1.

Although flow measured in some agricultural drains may include tributary inflow, such inflow to the Island Drain is minor. Twenty-four measurements of flow in the Island Drain were used to constrain drain-bed hydraulic conductance in the regression.

Parameter Estimation

Parameter values representing aquifer properties and specified boundaries were estimated through nonlinear regression that minimized differences between measured and computed heads and flows in a 94-year transient-state simulation from 1903 through 1996. Hydraulic heads computed in a steady-state



Shaded-relief map from U.S. Geological Survey
30-meter Digital Elevation Models

Figure 11. Locations of head measurements, stream segments, agricultural drains, and model faults.

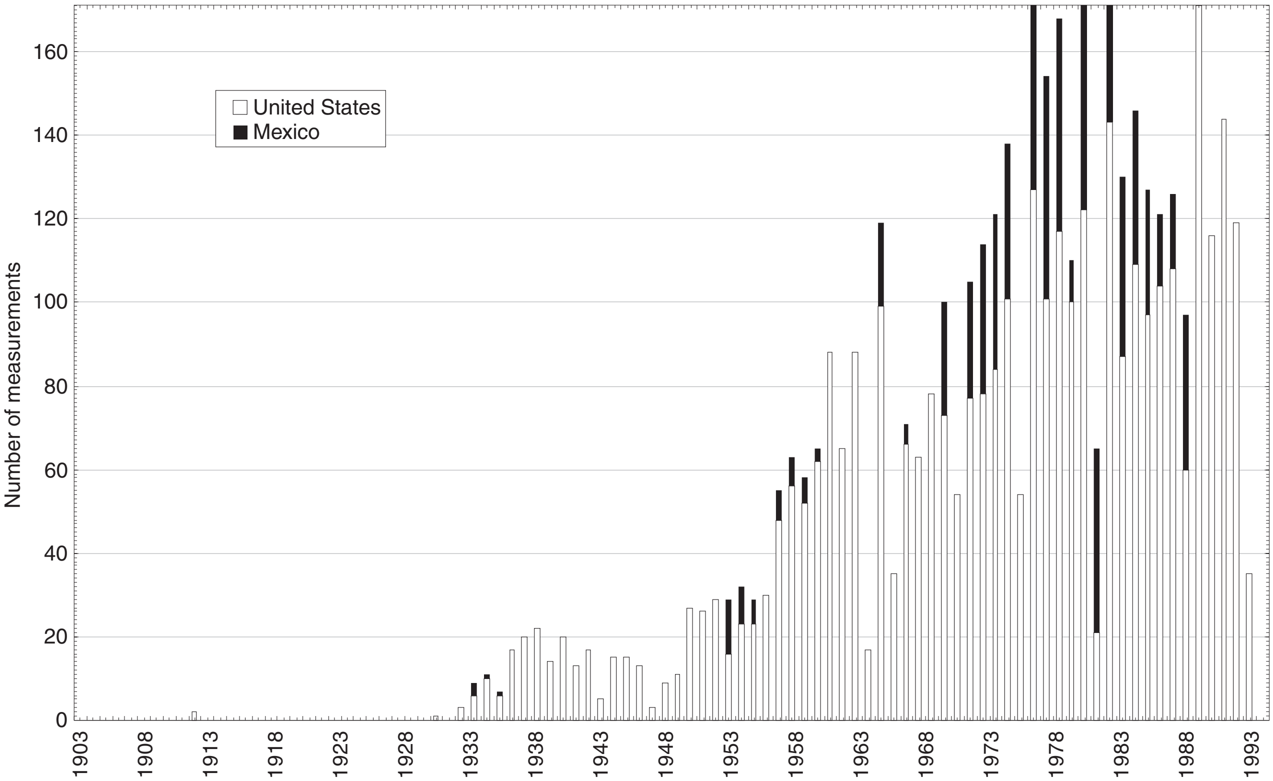


Figure 12. Number of annual head measurements in wells included in the nonlinear regression used in the ground-water flow model.

simulation representing prepumping conditions, when no large stresses were imposed on the aquifer system, provide initial conditions for the transient-state simulation. The nonlinear regression procedure was implemented using UCODE, in which sensitivities of model parameters are estimated through a perturbation technique (Poeter and Hill, 1998). Although MODFLOWP provides a similar regression procedure in which sensitivities of model parameters are computed directly from an analytical expression, a major limitation prevented its application for model calibration. Conversion from confined to unconfined conditions caused by dewatering the upper part of the modeled area can be represented in MODFLOWP in the solution for hydraulic head, but this conversion was not implemented in MODFLOWP for the regression procedure. The calibration procedure selected to circumvent this problem entailed (1) using MODFLOWP to define the parameter values in the model and compute hydraulic heads and flows and (2) running UCODE to estimate the optimum parameter values.

Improvements in model results were identified by comparing the sum of squared errors (*SSE*):

$$SSE = \Sigma[w_i^{1/2} e_i]^2 \text{ , } i = 1, n \qquad (9)$$

where e_i = difference between measured and calculated values of measurement *i*;
$w_i^{1/2}$ = square root of the weight assigned to the error in the measured value of measurement *i*;
$w_i^{1/2} e_i$ = weighted residual corresponding to measurement *i*; and
n = number of measurements;

and the standard error of estimate (SEE):

$$SEE = \left[\frac{SSE}{n-p}\right]^{1/2} \text{ , } \qquad (10)$$

where p = number of model parameters estimated by the regression.

The weights, w_i, were chosen according to procedures in Hill (1992) to account for the different units associated with head measurements (m) and flow measurements (m^3/d). The water-level altitudes reported for wells in the United States used a datum consistent with other data in the flow model. Heads in the United States were generally measured several days after the cessation of pumping in wells to better represent nonpumping conditions. The time elapsed after cessation of pumping is not known for wells in Mexico, however, and the reported water-level altitudes are less certain. The w_i values were therefore adjusted so that heads in wells in Mexico were weighted 33 percent less than heads in wells in the United States. Heads measured in the United States were weighted equally. Flow measurements were weighted to reflect the relative accuracy of Rio Grande and canal seepage-loss measurements and drain-flow measurements. Measurements of Rio Grande seepage loss (table 1) were weighted equally to heads measured in wells in the United States. Measurements of Franklin Canal seepage loss and flow in the Island Drain were weighted 67 percent less than measurements of Rio Grande seepage loss.

MODEL EVALUATION AND SIMULATION RESULTS

The spatial distribution of horizontal and vertical hydraulic conductivities was defined by assigning zones to each of the hydrogeologic facies, to which corresponding parameters representing hydraulic conductivities were applied. The horizontal extent of the recent alluvial facies (fig. 3) is known because deposition was constrained by the topography of the Rio Grande Valley. Boundaries between the fluvial, lacustrine-playa, and alluvial-fan facies are less constrained. Two possible geometries for the boundary between the fluvial and lacustrine-playa facies were tested: (1) a "block" model with a vertical facies boundary and (2) a "wedge" model in which the facies boundary sloped down to the west so that lacustrine-playa facies underlie the fluvial facies in parts of layers 2 through 9. In both models, the lacustrine-playa facies accommodated all of layer 10 and the hydraulic conductivities between the two facies were gradational, simulating some facies interfingering. For each model, the parameter-estimation regression was run to determine the lowest SSE parameter set. The resulting parameter sets for these two models differed only slightly. The "block" model was found to have lower overall error; the geometry of this hydraulic-conductivity distribution is depicted in cut-away perspective in figure 4. Although the horizontal hydraulic conductivities of the alluvial-fan and fluvial facies were independently estimated, they converged to essentially identical values. This suggests that the location of this facies boundary may not be significant in the context of the ground-water flow model.

The total SSE computed using equation 7 was 38,814 m^2. The SSE for all model heads computed with equation 8 was 2.99 m^2. The SSE for heads in United States wells was 2.90 m^2 and for heads in Mexican wells was 3.44 m^2. Scatter plots of simulated heads in relation to measured heads and of simulated heads in relation to weighted residuals for wells in Mexico and the United States are shown in figure 13C-D. The scatter plots for the United States wells show no obvious evidence of model bias. The scatter plot of simulated heads in relation to weighted residuals for wells in Mexico suggests some bias toward negative weighted residuals. This bias indicates that heads in Mexican wells are, in general, slightly lower than those predicted by the ground-water flow model.

Estimates of Aquifer Properties

The best-fit parameter values along with their 95-percent confidence intervals computed from the nonlinear least-squares regression of the "block" facies model are summarized in table 3. Because the lengths of the Rio Grande, Franklin Canal, Acequia Madre, and agricultural drains in each model cell are well known but the thickness of bed material is uncertain, these parameters are reported as a conductance per unit length. Quaternary fault-zone hydraulic conductivity was estimated on the basis of a fault-zone thickness of 1 m. If actual fault-zone thickness is on the order of 10 or 1 cm, the actual fault-zone hydraulic conductivity is one or two orders of magnitude smaller, respectively.

Parameter Sensitivities

Composite scaled sensitivities (Hill, 1998) are listed in table 2 for model parameters estimated in the nonlinear regression. These sensitivities vary somewhat as a function of parameter values and distribution. The sensitivities are useful for interpreting

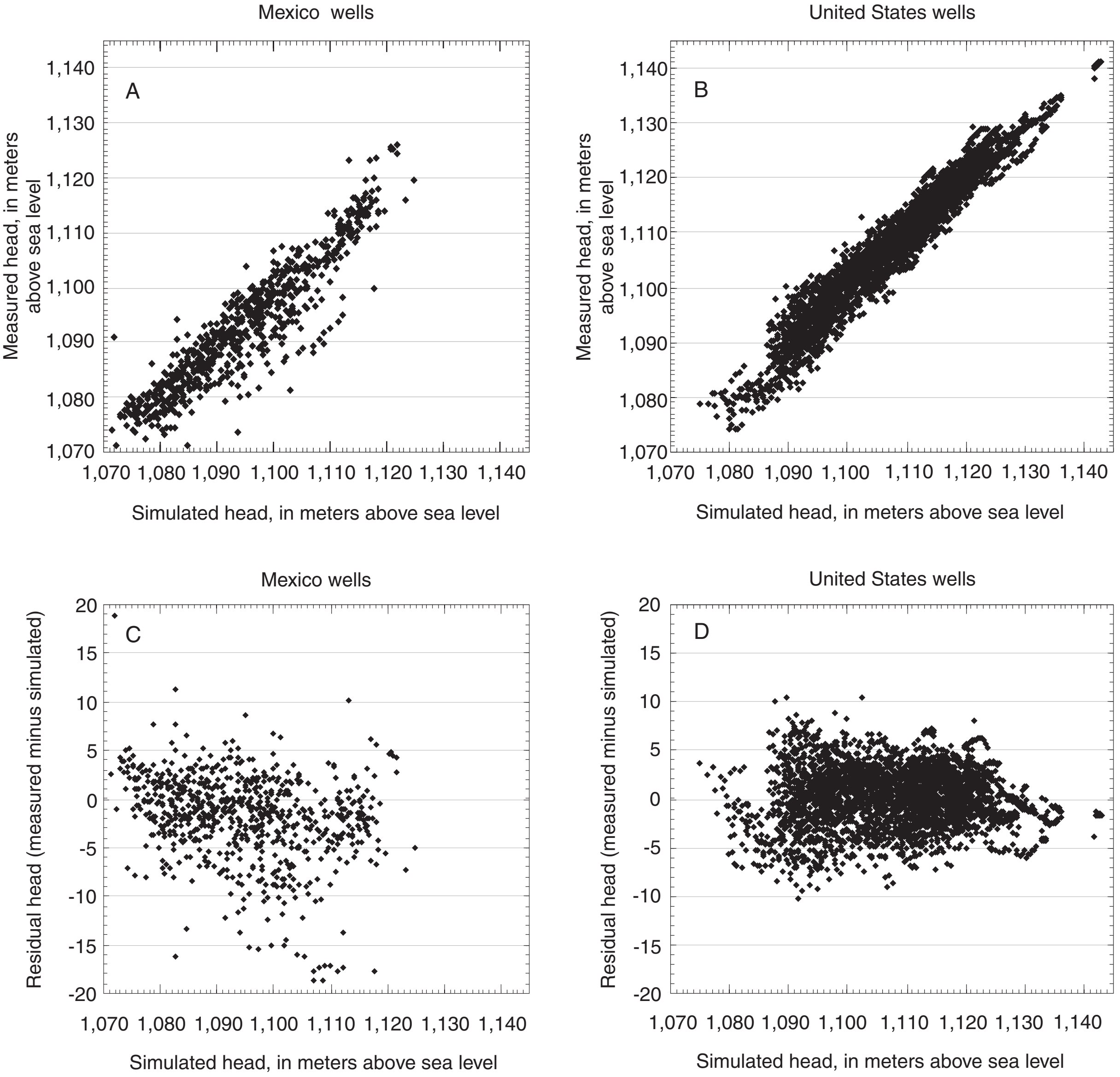


Figure 13. Simulated and measured heads and weighted residuals computed in transient-state simulation of the Hueco Bolson.

Table 3. Optimum parameter values estimated for Hueco Bolson aquifer, through nonlinear regression in transient-state simulation, and their approximate 95-percent confidence intervals

[m, meters; m/d, meters per day; m^3/d, cubic meters per day; N/A, not applicable]

Parameter	Value	Confidence interval	Scaled sensitivity, in meters
Recharge:			
Irrigation-return flow[1]	3.8×10^4 m^3/d	2.2×10^4 - 6.5×10^4 m^3/d	0.3
Underflow from Tularosa Basin	2.0×10^4 m^3/d	1.9×10^4 - 2.2×10^4 m^3/d	7
Mountain front on alluvial fans[2]	8.0×10^2 m^3/d	0 - 2×10^3 m^3/d	2
Underflow from Mesilla Basin	3.4×10^2 m^3/d	Not estimated	N/A
Horizontal hydraulic conductivity:			
Alluvial-fan facies	6.8 m/d	6.0 - 7.7 m/d	5
Recent fluvial sediments	4.0 m/d	2.8 - 7.2 m/d	2
Fluvial and alluvial facies	6.8 m/d	6.4 - 7.2 m/d	10
Lacustrine-playa facies	0.9 m/d	0.5 - 1.4 m/d	0.3
Quaternary faults	3.8×10^{-3} m/d	1×10^{-3} - 1×10^{-2} m/d	8
Vertical hydraulic conductivity:			
Alluvial-fan facies	1.2×10^{-3} m/d	6×10^{-4} - 2×10^{-3} m/d	3
Recent fluvial sediments	1.3×10^{-1} m/d	6×10^{-2} - 6×10^{-1} m/d	2
Fluvial and alluvial facies	1.3×10^{-2} m/d	1×10^{-2} - 1.5×10^{-2} m/d	0.6
Lacustrine-playa facies	2.5×10^{-2} m/d	6×10^{-3} - 1×10^{-1} m/d	0.4
Specific yield	0.178	0.173 - 0.184	10
Specific storage - elastic	7×10^{-6} m^{-1}	2×10^{-6} - 1×10^{-5} m^{-1}	0.5
Specific storage - inelastic	7×10^{-5} m^{-1}	Not estimated	N/A
Conductance per unit length:			
Rio Grande	1.8 m/d	1.6 - 2.0 m/d	1
Agricultural drains	5.8 m/d	2 - 1.6×10^1 m/d	2
Irrigation canals	3.0 m/d	Not estimated	N/A
Evapotranspiration extinction depth	5 m	Not estimated	N/A
Maximum evapotranspiration rate	4.6×10^{-3} m/d	1×10^{-3} - 7×10^{-3} m/d	2
Manning's *n:*			
Rio Grande	0.03	Not estimated	N/A
Franklin Canal, Acequia Madre	0.004	Not estimated	N/A

[1] Maximum for normal irrigation year after 1933.

[2] Distributed in arroyos below Organ, Franklin, and Juarez Mountains.

relative sensitivities between model parameters and the relative importance of a parameter in reducing model error in the nonlinear regression. Specific yield of unconfined layers and horizontal hydraulic conductivity of the fluvial facies were the most sensitive model parameters, followed by recharge underflow from the Tularosa Basin and conductance of Quaternary fault zones.

Water-Level Drawdowns

Simulated water-table altitudes for 1902 (steady-state conditions) and for 1958, 1973, and 1980 (transient-state conditions) are contoured at 2-m intervals and shown in figure 14A-D. The progressive growth of cones of depression under El Paso and Ciudad Juarez is evident from 1958 through 1980. Shallow ground water flows away from the Rio Grande toward these cones of depression on either side of the international border.

Potentiometric surface altitudes computed for model layer 5, which is approximately 135 m (440 ft) below the steady-state water table, for 1958, 1973, 1980, and 1996 are shown in figure 15A-D. This model layer is in the middle of the depth interval in which many production wells are screened in the Hueco Bolson. The contours for 1958 through 1996 show the expanding cones of depression under El Paso and Ciudad Juarez; the Rio Grande, however, has much less influence at this depth than at the water table. Since about 1980 (fig. 15C), water at this depth generally flows from north to south beneath the river toward the lower potentiometric heads beneath Ciudad Juarez. By 1973, ground-water drawdown under Ciudad Juarez had created a ground-water divide to the southeast, which isolated ground-water flow near the city from the regional pattern of southeast flow. This divide has migrated farther to the southeast as the cone of depression has deepened. The influence of simulated Quaternary faults (fig. 11) becomes increasingly evident as deflections of water-level contours in later transient stress periods, such as depicted for 1980 and 1996 (fig. 15C,D).

The three-dimensional pattern of ground-water drawdown beneath El Paso and Ciudad Juarez is further illustrated by perspective views for 1973 and 1996 (fig. 16A,B). The vertical section of these images was sliced along an azimuth of N. 30° E. to transect the drawdown cones beneath both cities. Only active model cells are shown; missing cells in the El Paso and Ciudad Juarez regions in 1996 (fig. 16B) result from deactivation by ground-water drawdown beneath the bottom of model layer 1. Model layer 2 has similarly deactivated in some areas.

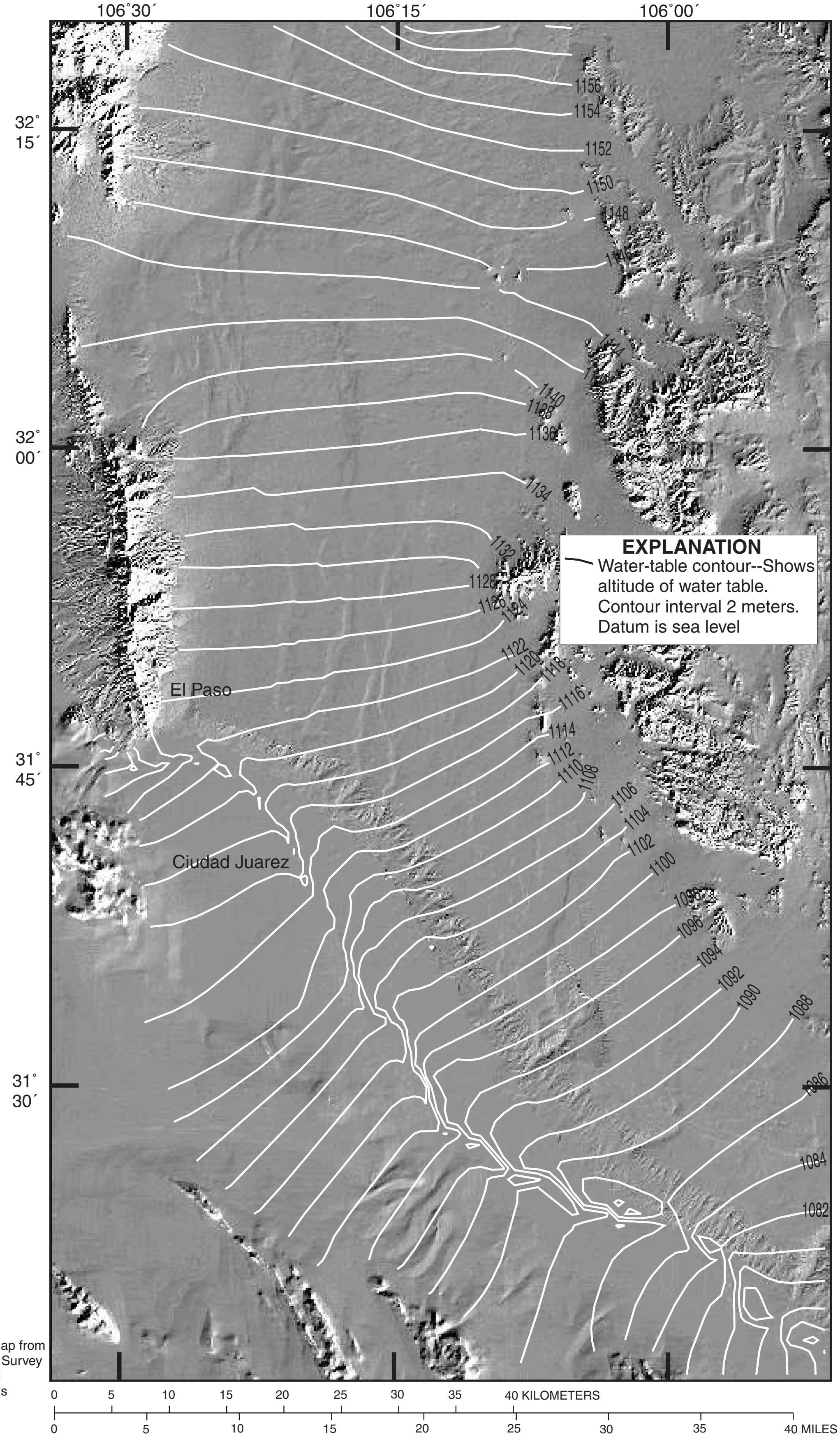
Hydrographs of measured and model-simulated water levels for 18 wells are presented in figures 17A-G. The locations of these wells, which are representative of the other 274 wells in the measurement set, are shown in figure 11. These hydrographs illustrate the general quality of model fit and may be useful for showing areas where the model could be improved. (A spreadsheet containing hydrograph measurements for the remaining 274 wells is available on request.)

Ground-Water Budget

Components of the ground-water budget that change during the course of the transient simulation are shown in figure 18. Water pumped from wells is supplied primarily by releases from ground-water storage, principally by drainage of aquifer pore space; this process results in large declines of the water table. The mirror relation between ground-water pumping and releases from storage is evident in figure 18A,B. A similar mirrorlike relation can be seen in figure 18C,D, which illustrates the principal budget components in the shallow portion of the aquifer system in the Rio Grande Valley. These two graphs indicate that Rio Grande water infiltrating into the shallow aquifer system is consumed primarily by ET and (or) flows to agricultural drains.

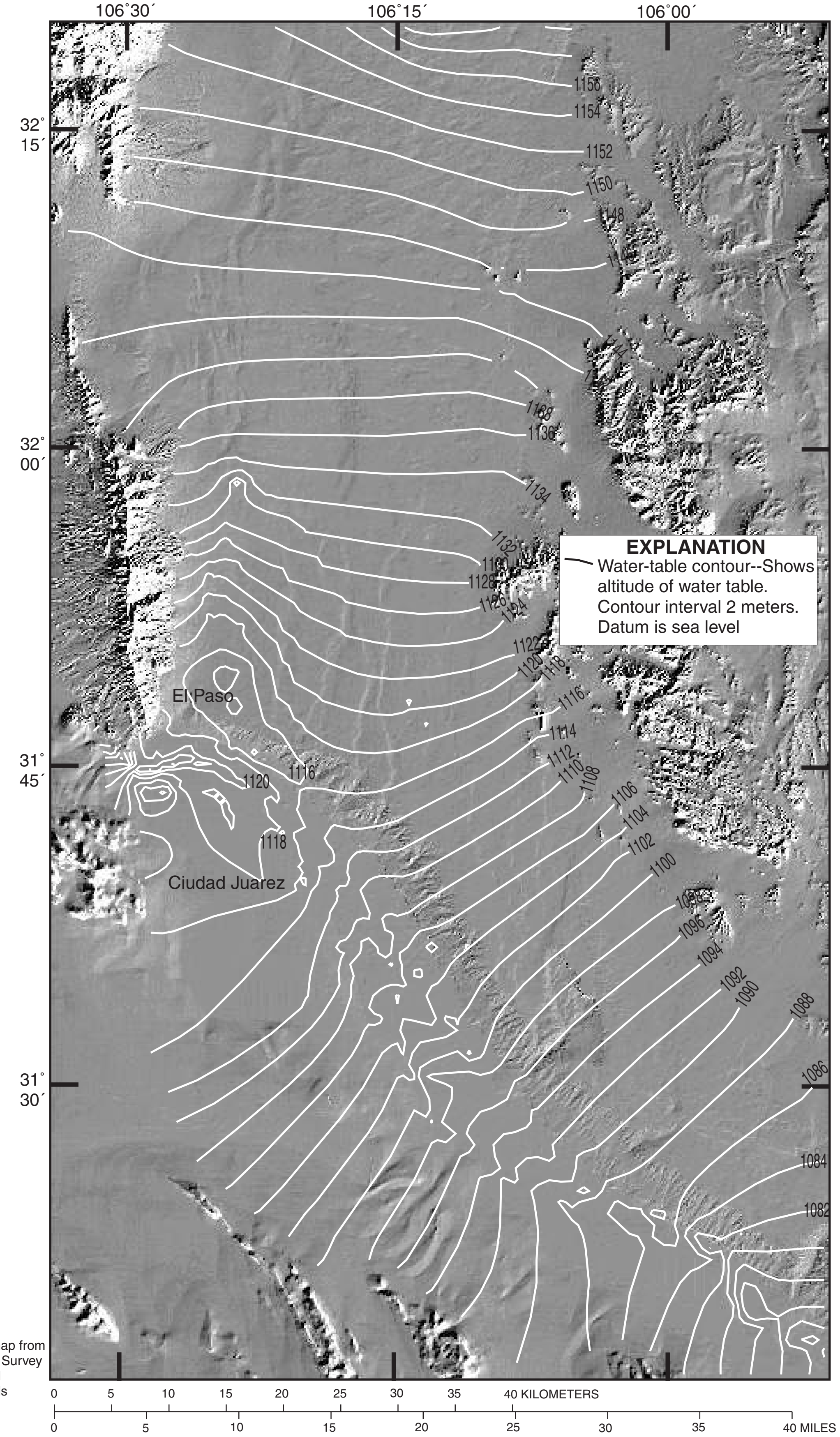
Seepage from the Rio Grande

The simulated seepage losses from the Rio Grande between the end of the Chamizal zone and Riverside Dam for two historical and one hypothetical (design flow) 5-year periods are depicted in figure 19A-D. Although model fluxes and other report figures have units in meters per day, these seepage losses are presented in acre-ft/yr for the benefit of interested parties. Variations in seepage by month from 1975 to 1979 and 1988 to 1992 are shown in figure 19A. Annual seepage loss was divided into seepage during the primary and secondary irrigation seasons in figure 19B-D. Seepage losses for 1975-79 and 1988-92 were during times of relatively low and high flow in the Rio Grande, respectively, and correspond to the monthly periods illustrated in figure 10. The greater seepage in 1988-92 principally results from higher average stage of the Rio Grande.



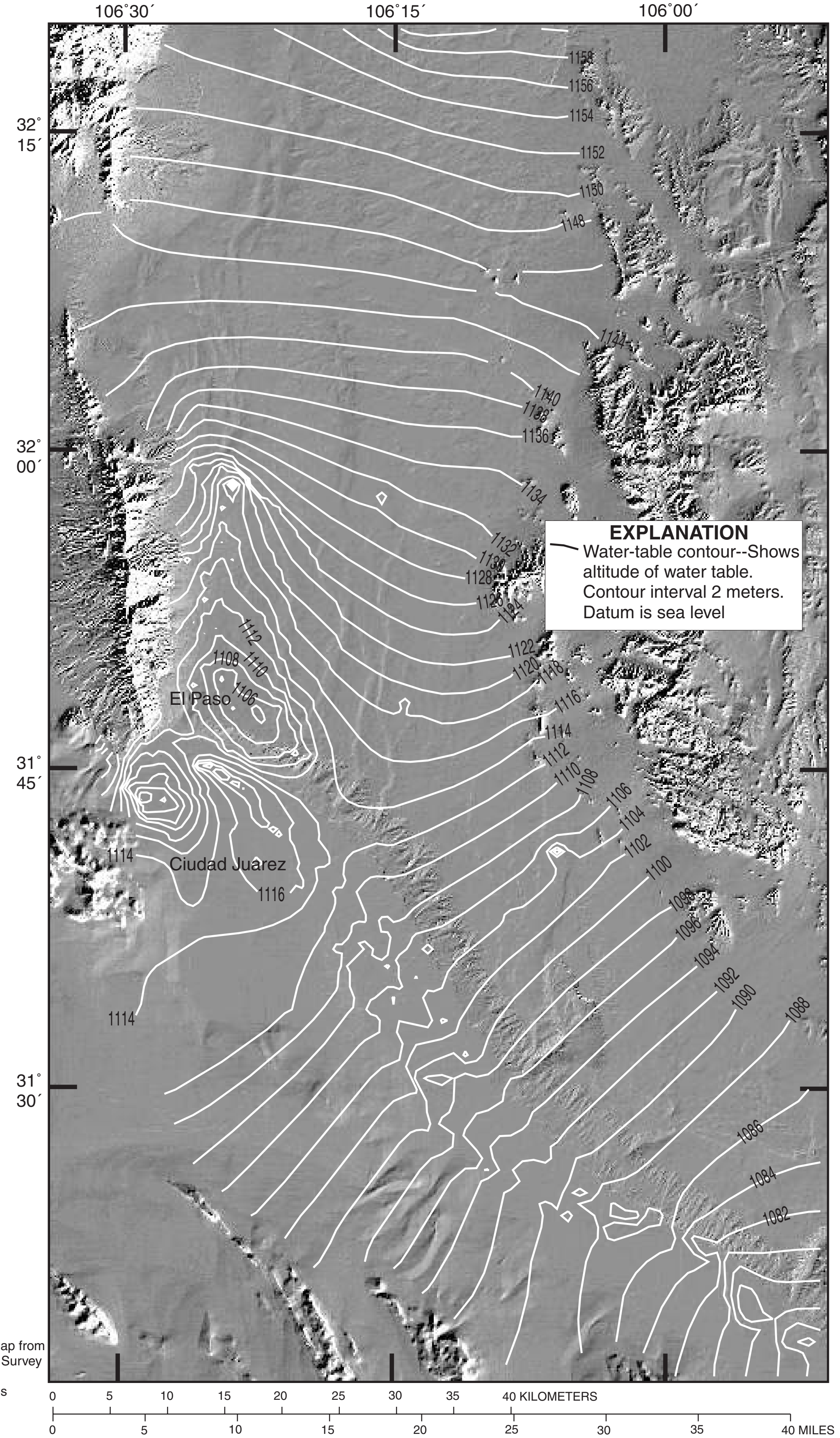
Shaded-relief map from U.S. Geological Survey 30-meter Digital Elevation Models

Figure 14A. Simulated water table in shallow aquifer (model layers 1 and 2) in 1902 (steady-state conditions).



Shaded-relief map from
U.S. Geological Survey
30-meter Digital
Elevation Models

Figure 14B. Simulated water table in shallow aquifer (model layers 1 and 2) in 1958.

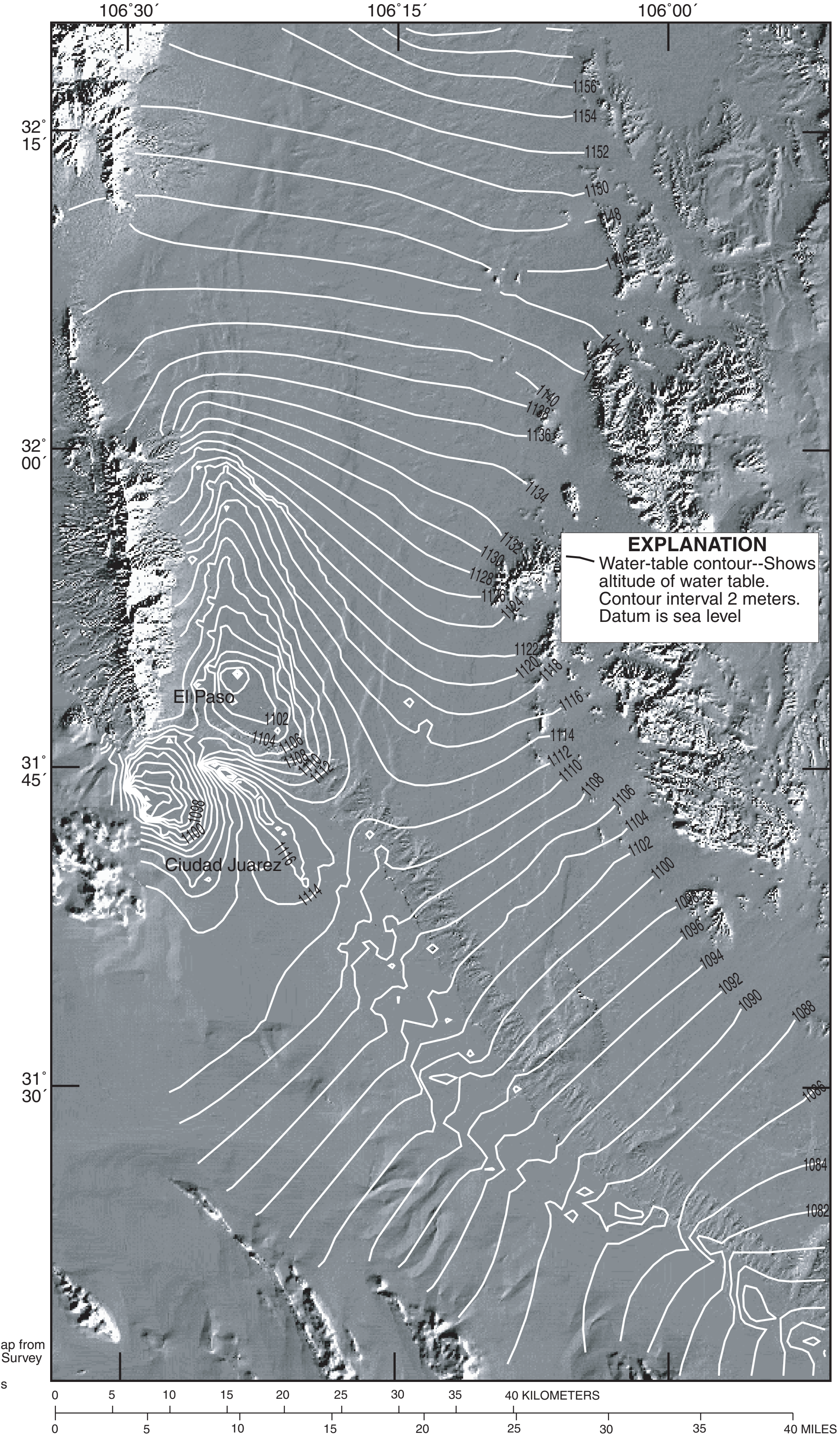


EXPLANATION

Water-table contour--Shows altitude of water table. Contour interval 2 meters. Datum is sea level

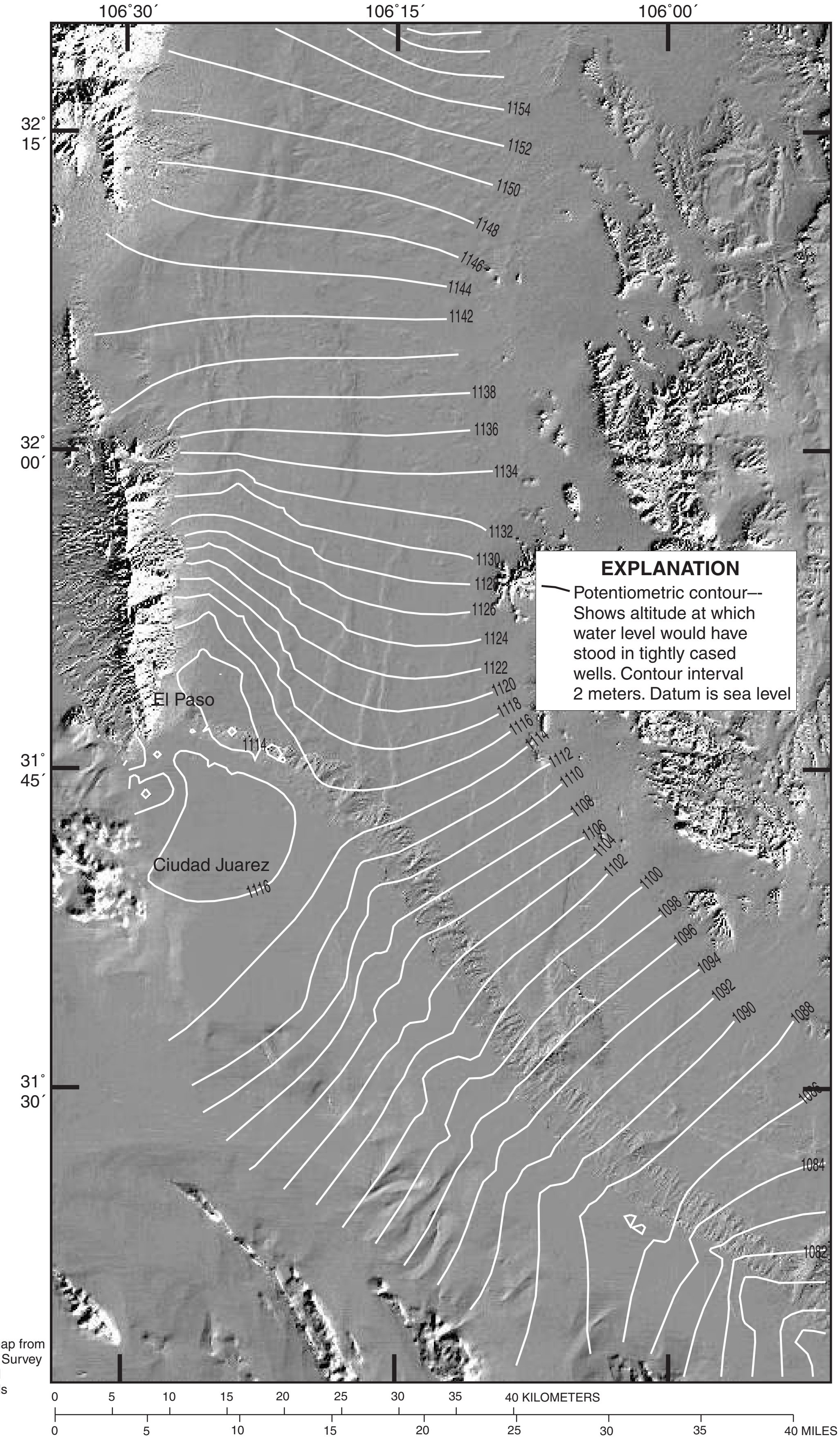
Shaded-relief map from U.S. Geological Survey 30-meter Digital Elevation Models

Figure 14C. Simulated water table in shallow aquifer (model layers 1 and 2) in 1973.



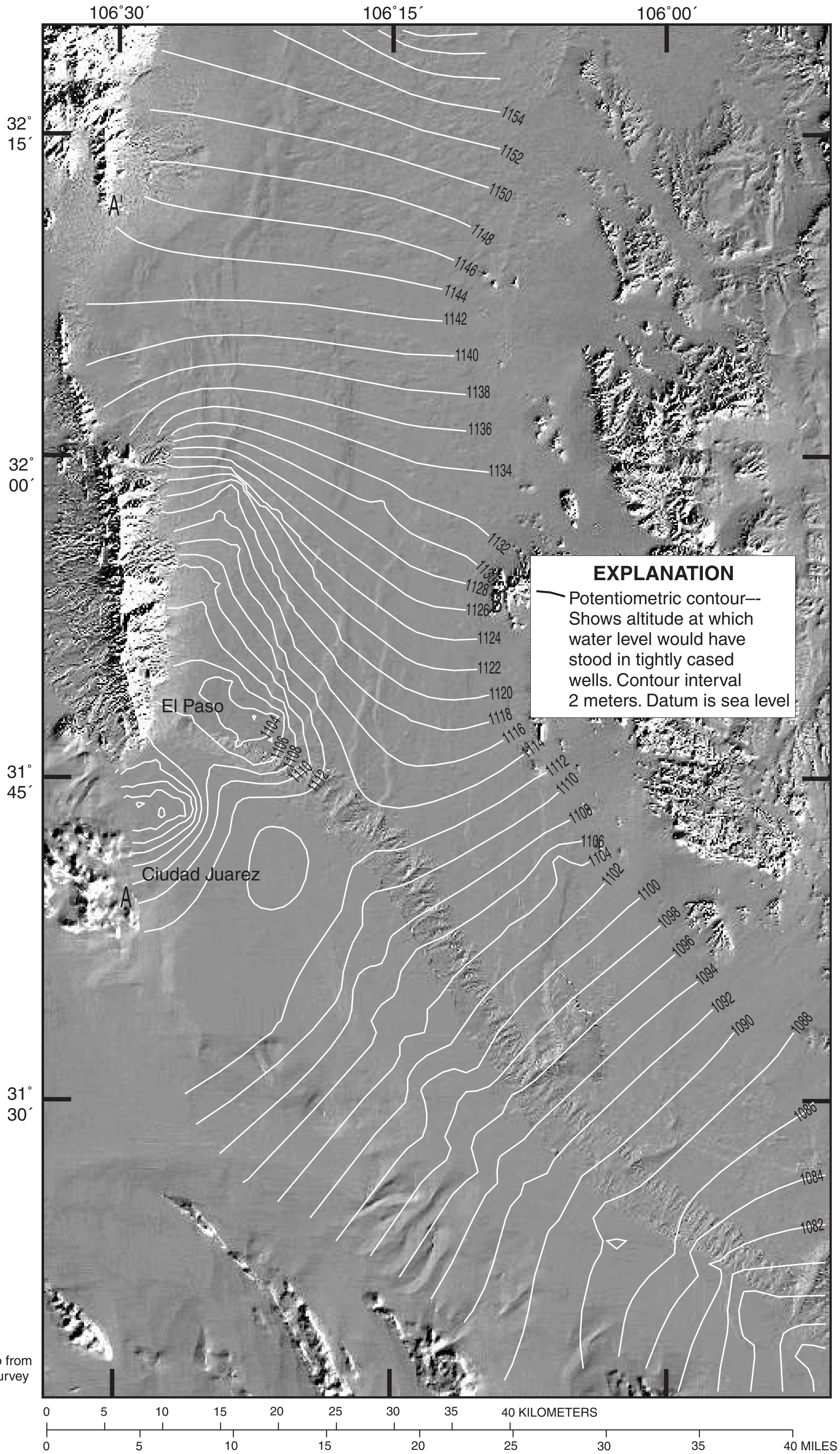
Shaded-relief map from U.S. Geological Survey 30-meter Digital Elevation Models

Figure 14D. Simulated water table in shallow aquifer (model layers 1 and 2) in 1980.



Shaded-relief map from U.S. Geological Survey 30-meter Digital Elevation Models

Figure 15A. Simulated potentiometric surface in model layer 5 in 1958.

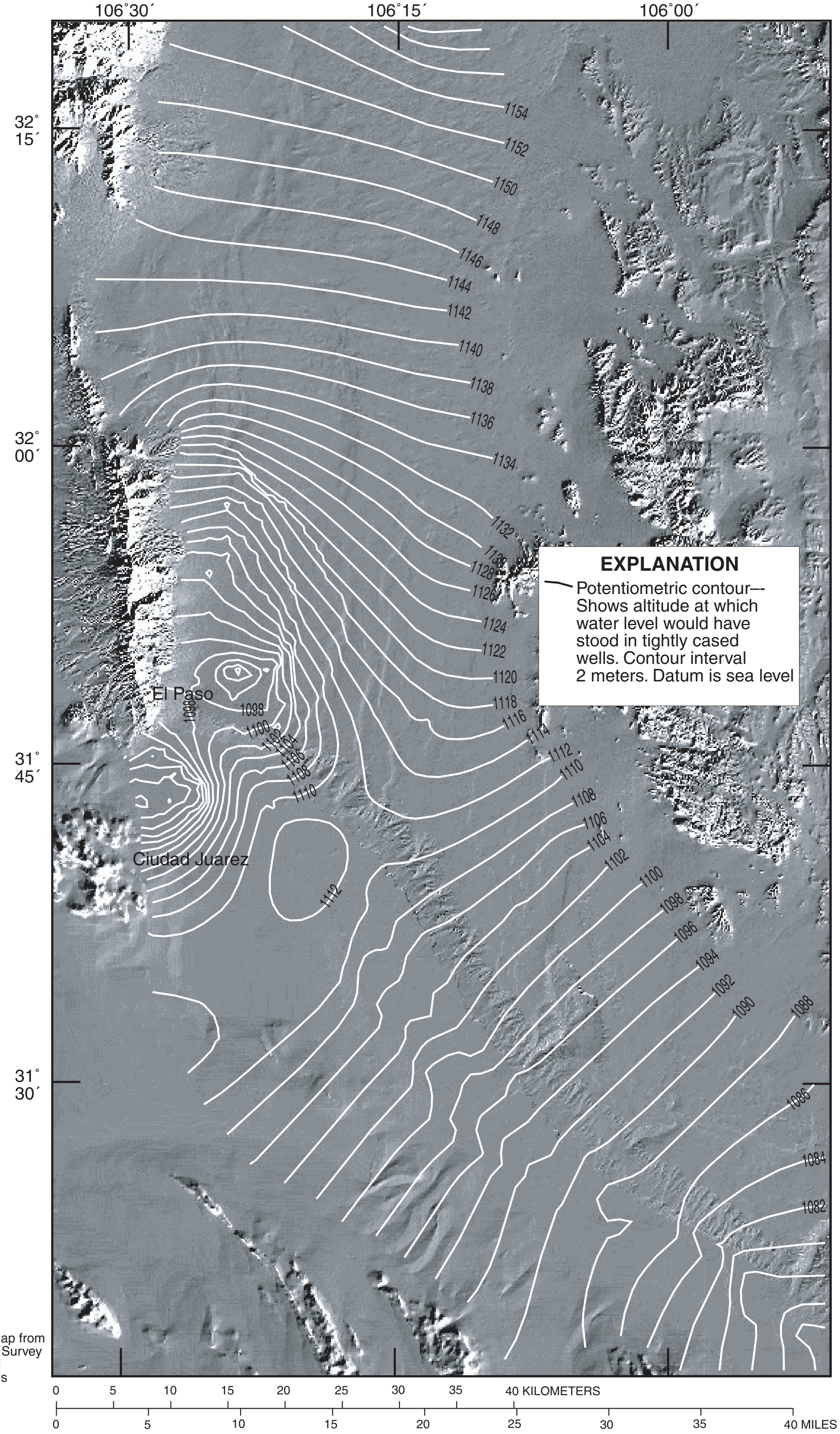


EXPLANATION

Potentiometric contour-- Shows altitude at which water level would have stood in tightly cased wells. Contour interval 2 meters. Datum is sea level

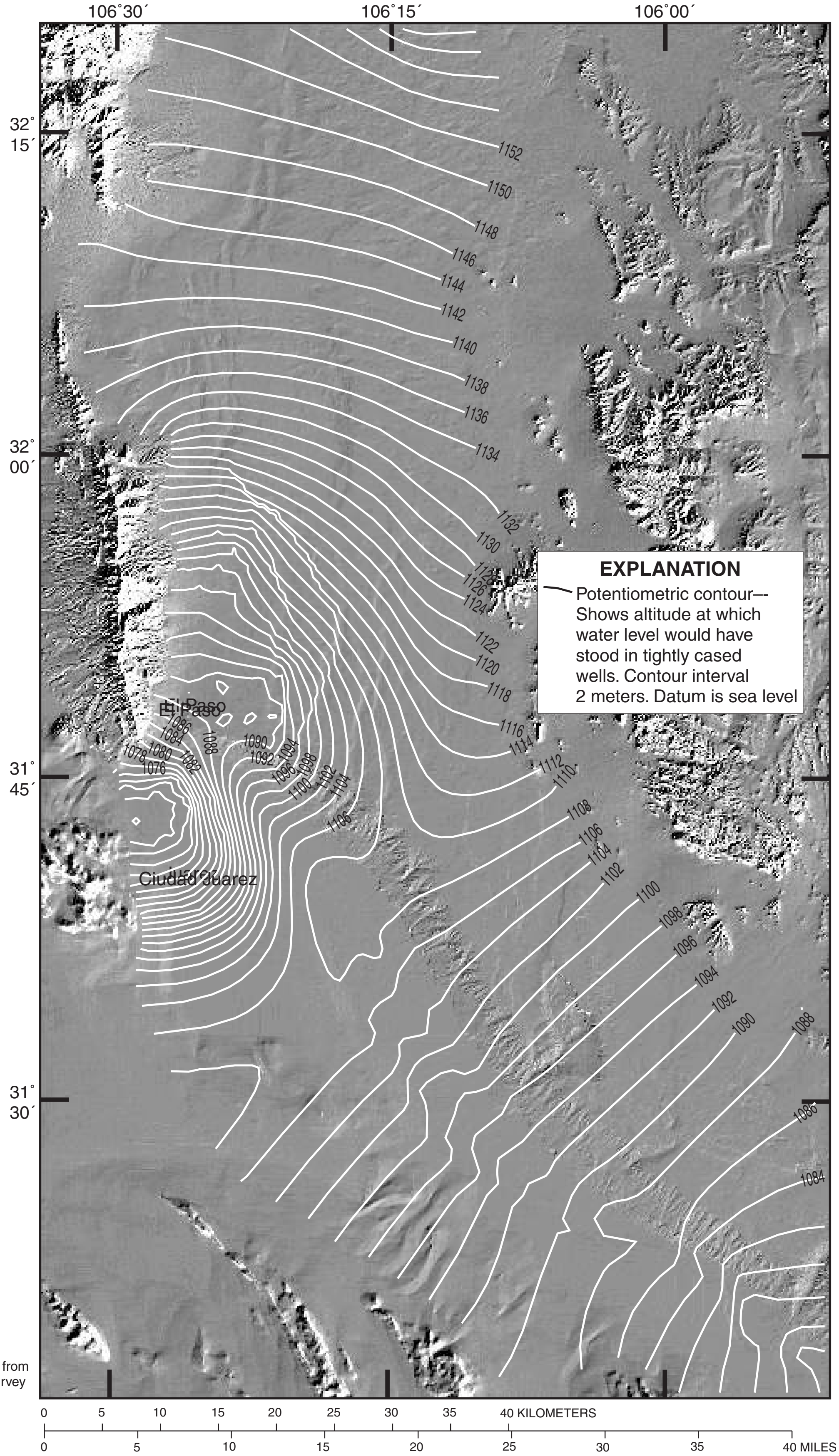
Shaded-relief map from U.S. Geological Survey 30-meter Digital Elevation Models

Figure 15B. Simulated potentiometric surface in model layer 5 in 1973.



Shaded-relief map from U.S. Geological Survey 30-meter Digital Elevation Models

Figure 15C. Simulated potentiometric surface in model layer 5 in 1980.



Shaded-relief map from U.S. Geological Survey 30-meter Digital Elevation Models

Figure 15D. Simulated potentiometric surface in model layer 5 in 1996.

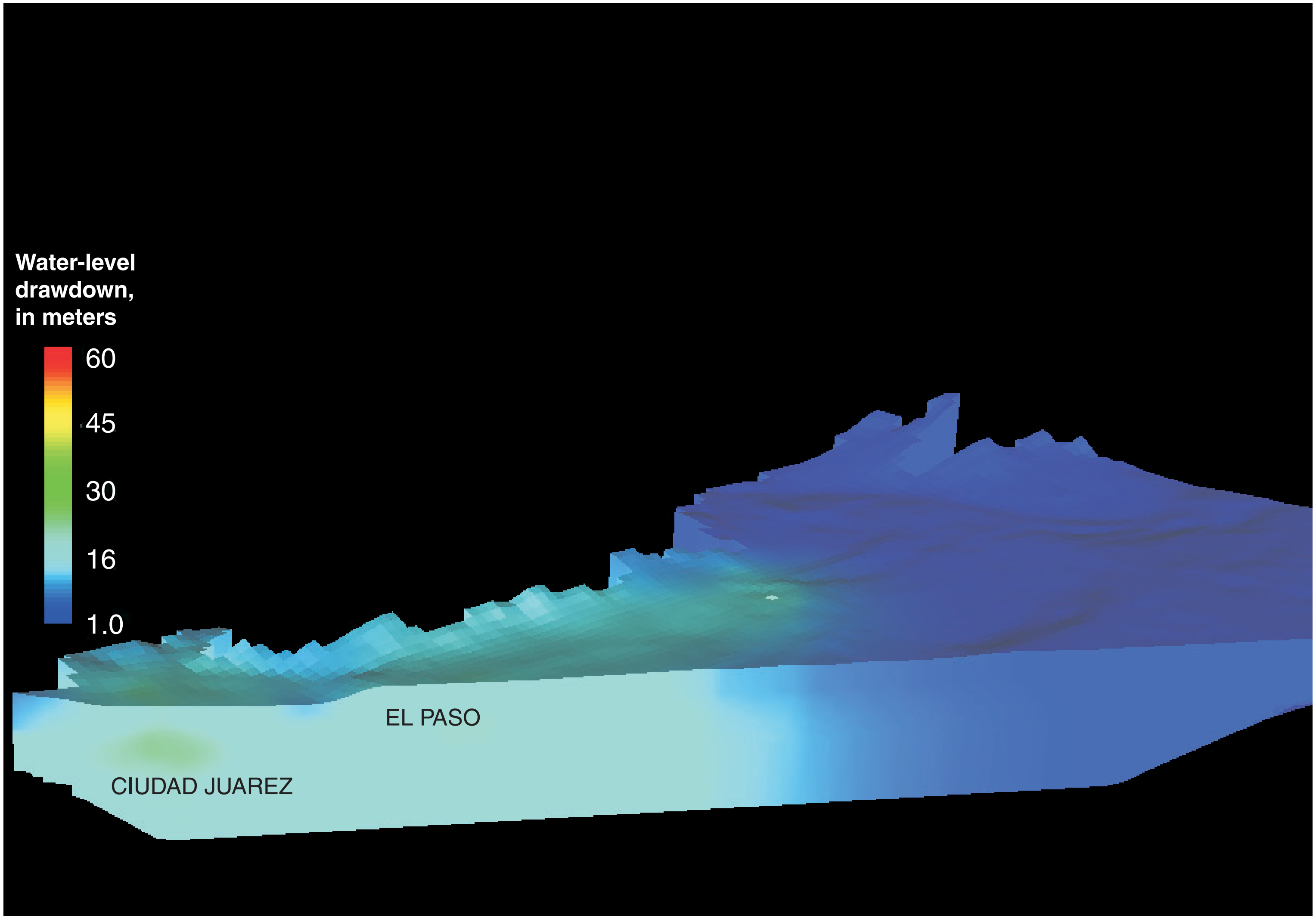


Figure 16A. Perspective view showing water-level drawdown in the Hueco Bolson aquifer in 1973. Logarithmic color scale.

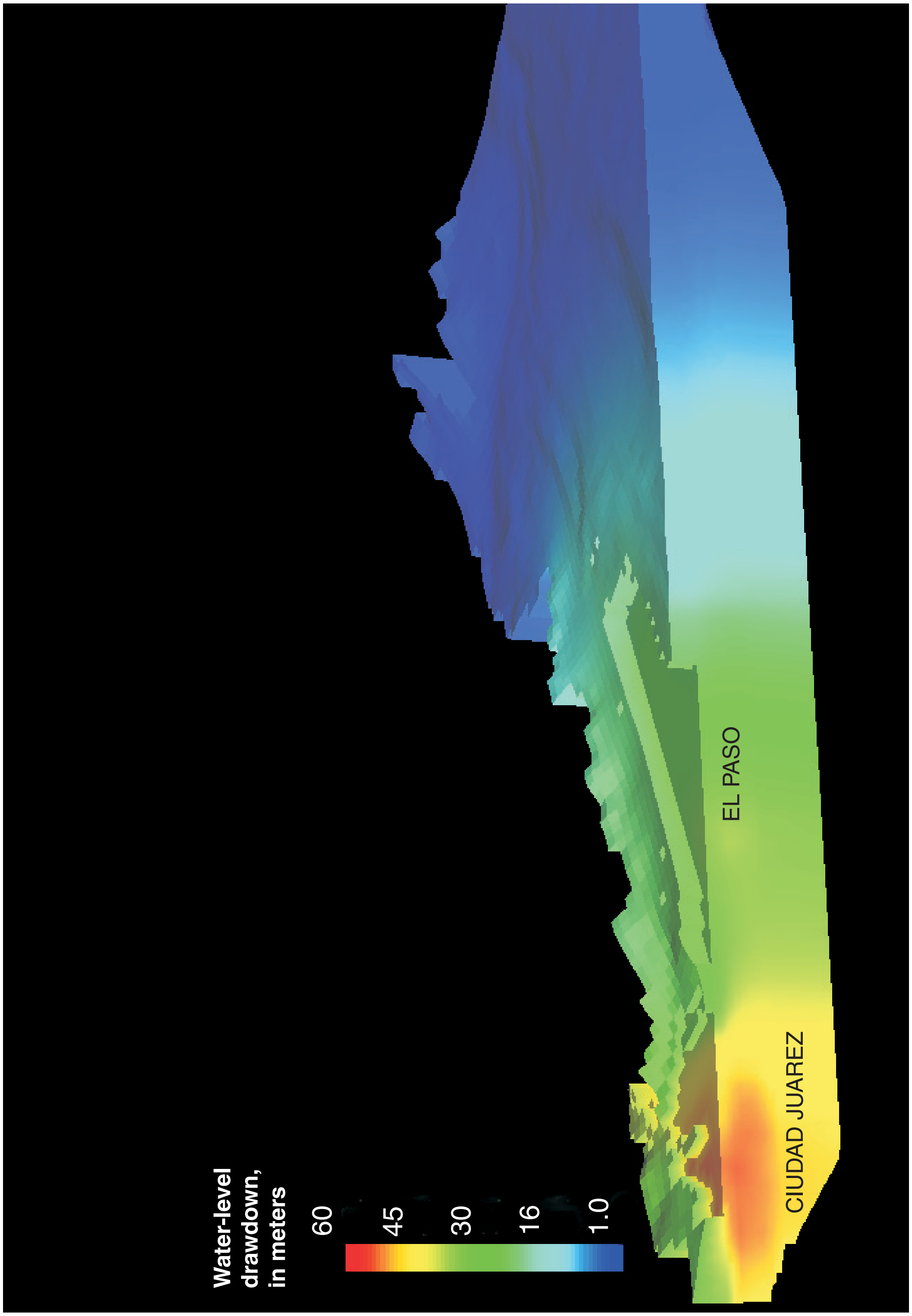


Figure 16B. Perspective view showing water-level drawdown in the Hueco Bolson aquifer in 1996. Logarithmic color scale.

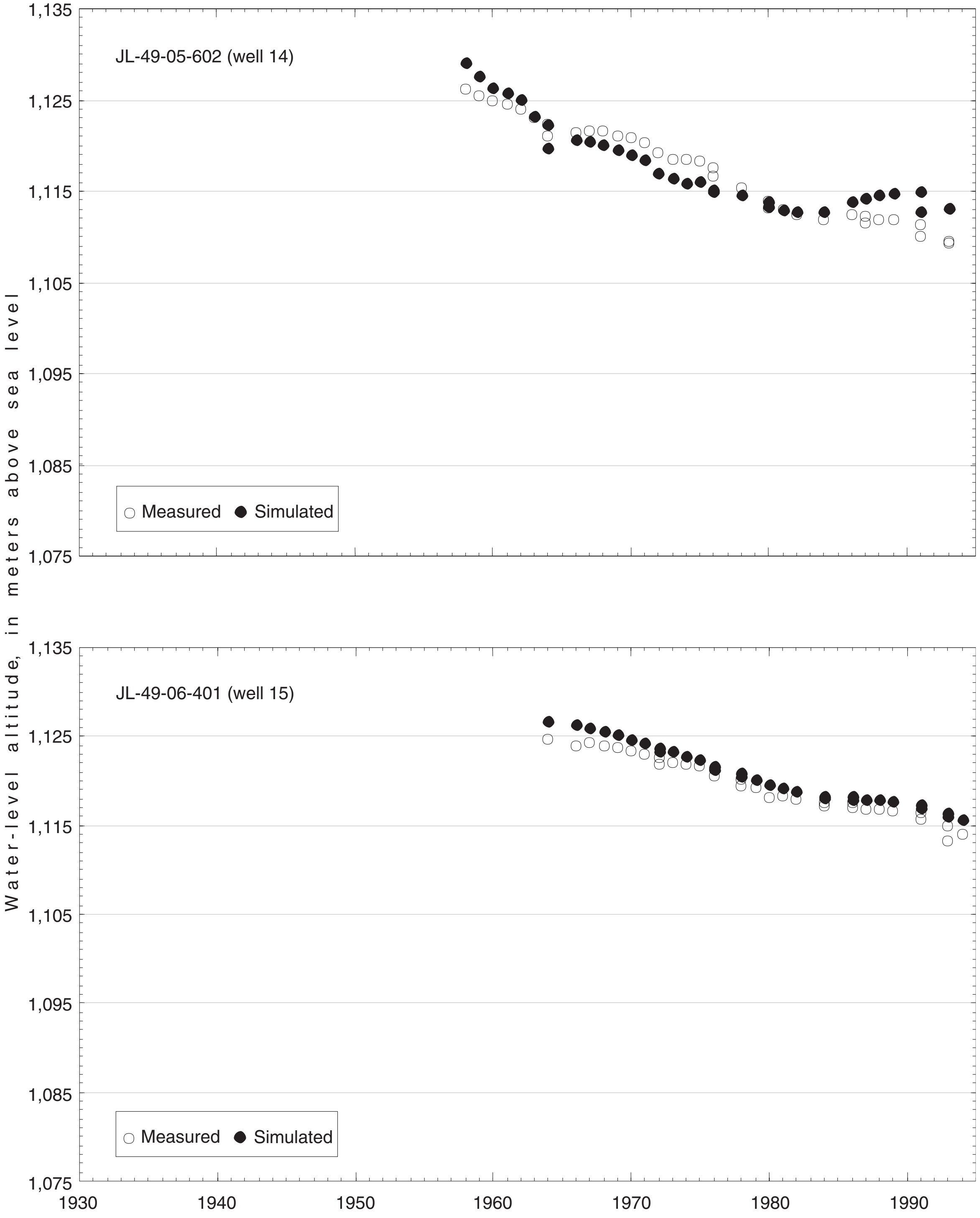


Figure 17A. Measured and simulated water levels from 1930 through 1995 in selected wells in the Mesa-Nevins well field (location of wells shown in figure 11).

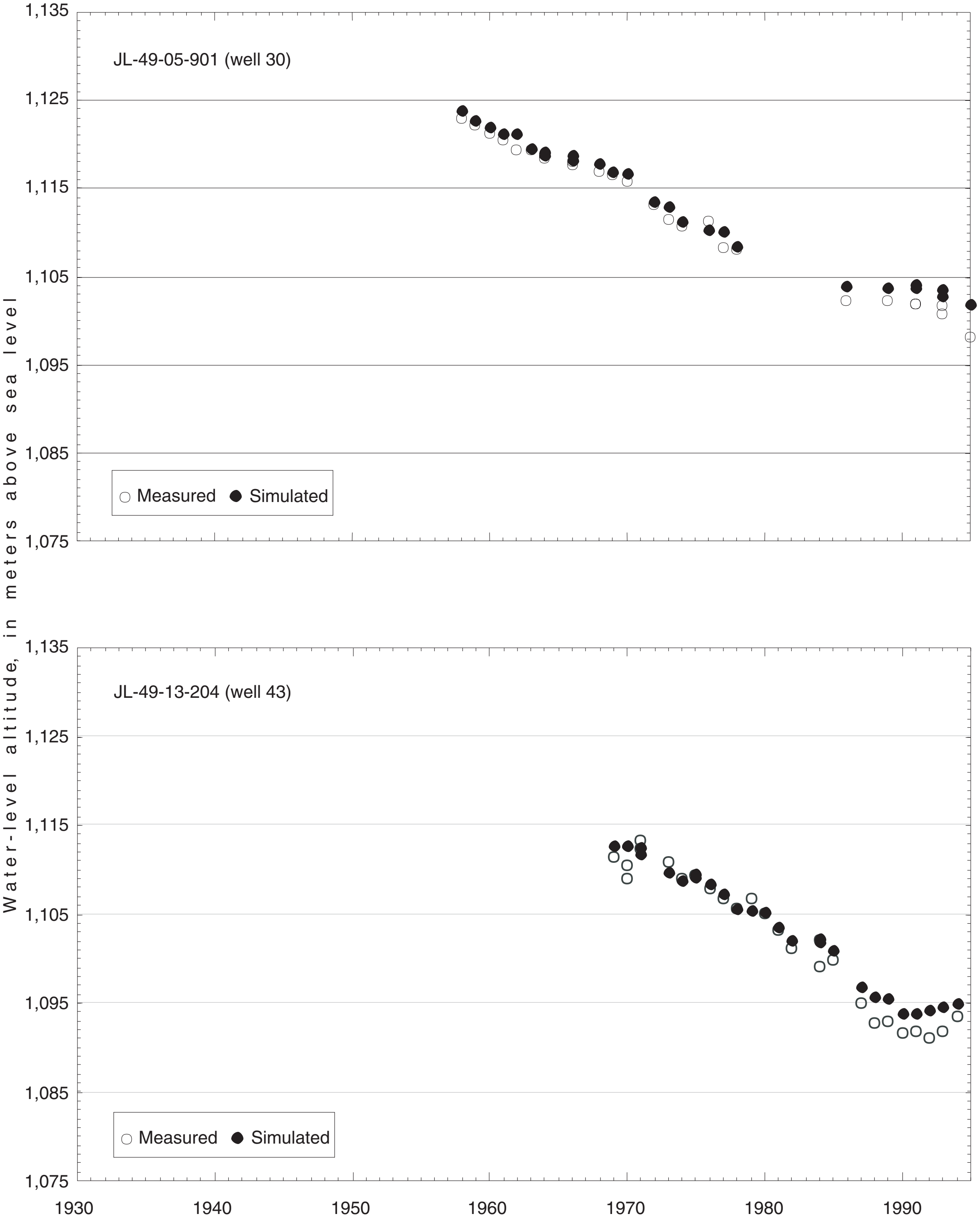


Figure 17A. Measured and simulated water levels from 1930 through 1995 in selected wells in the Mesa-Nevins well field (location of wells shown in figure 11)--Concluded.

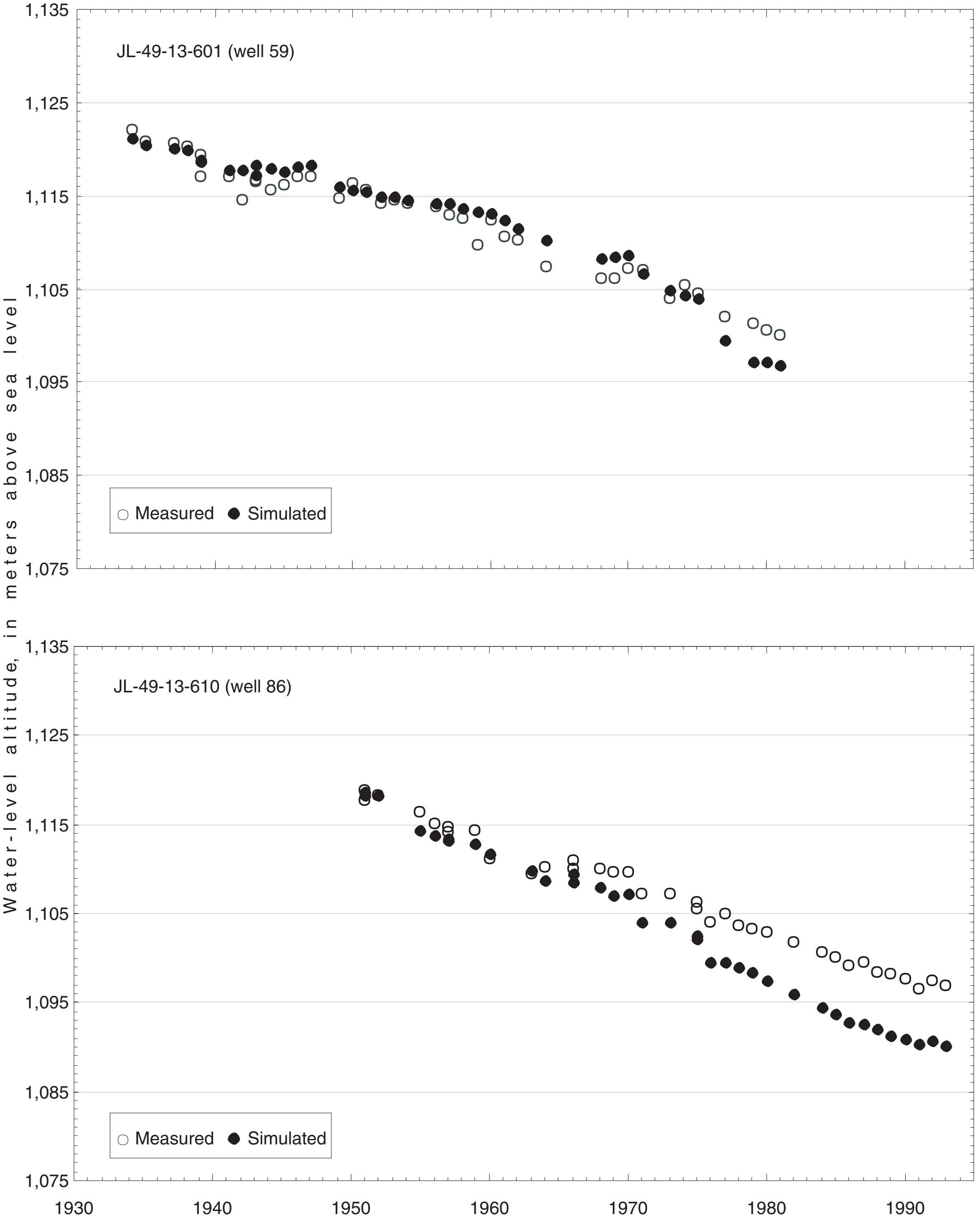


Figure 17B. Measured and simulated water levels from 1930 through 1995 in selected wells in the Airport well field (location of wells shown in figure 11).

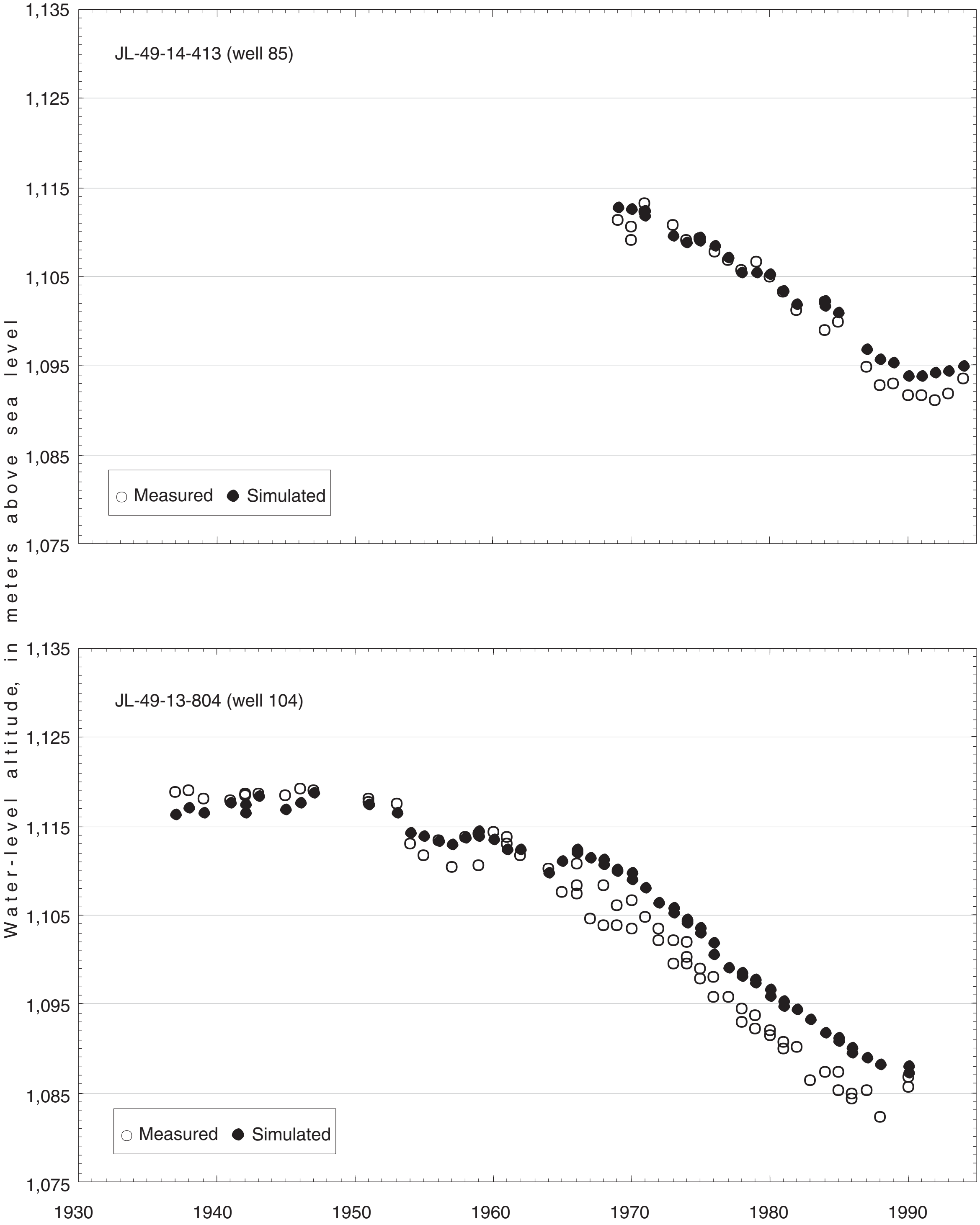


Figure 17C. Measured and simulated water levels from 1930 through 1995 in selected wells in the Cielo Vista and Town well fields (location of wells shown in figure 11).

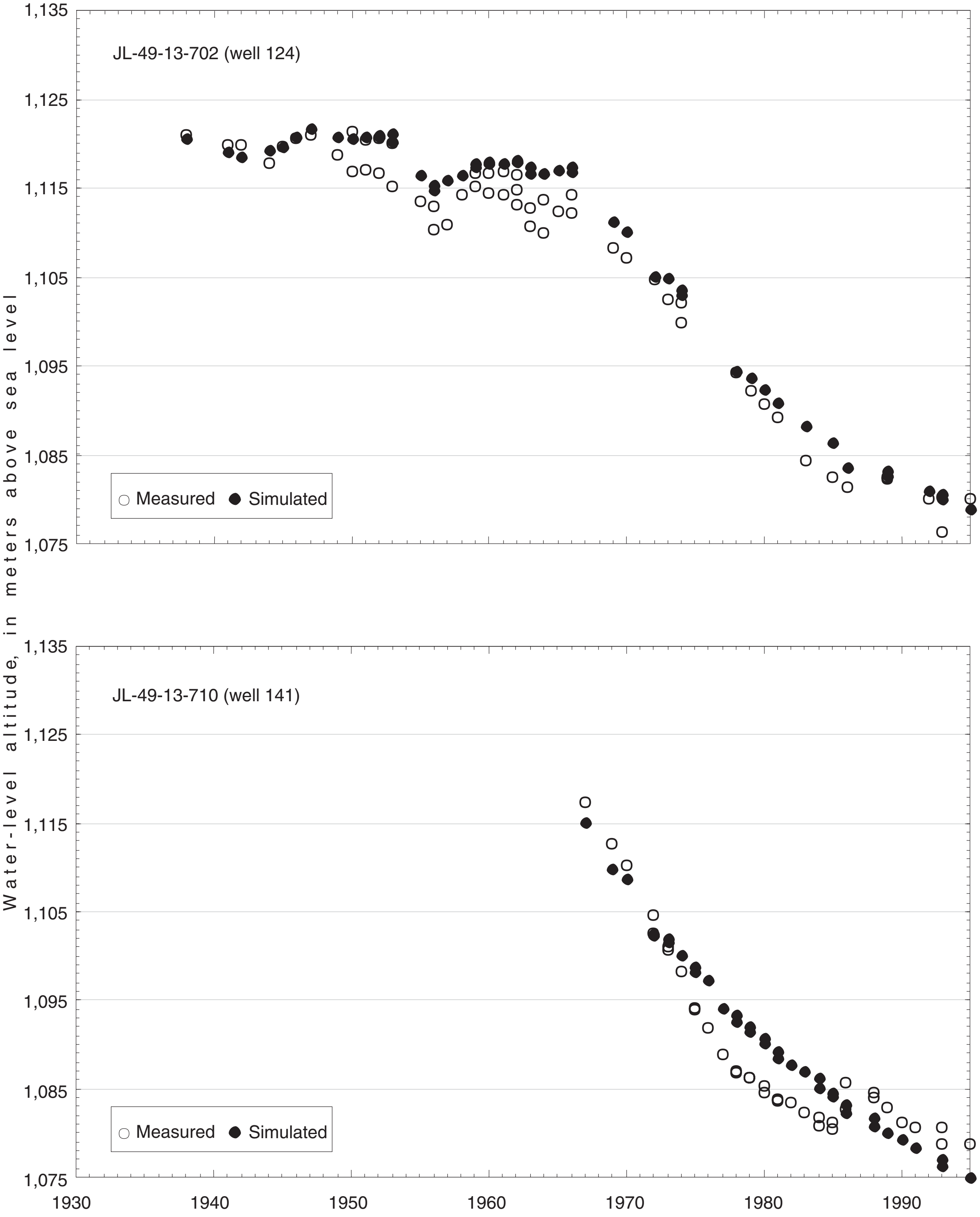


Figure 17D. Measured and simulated water levels from 1930 through 1995 in selected wells in the water-plant well field (location of wells shown in figure 11).

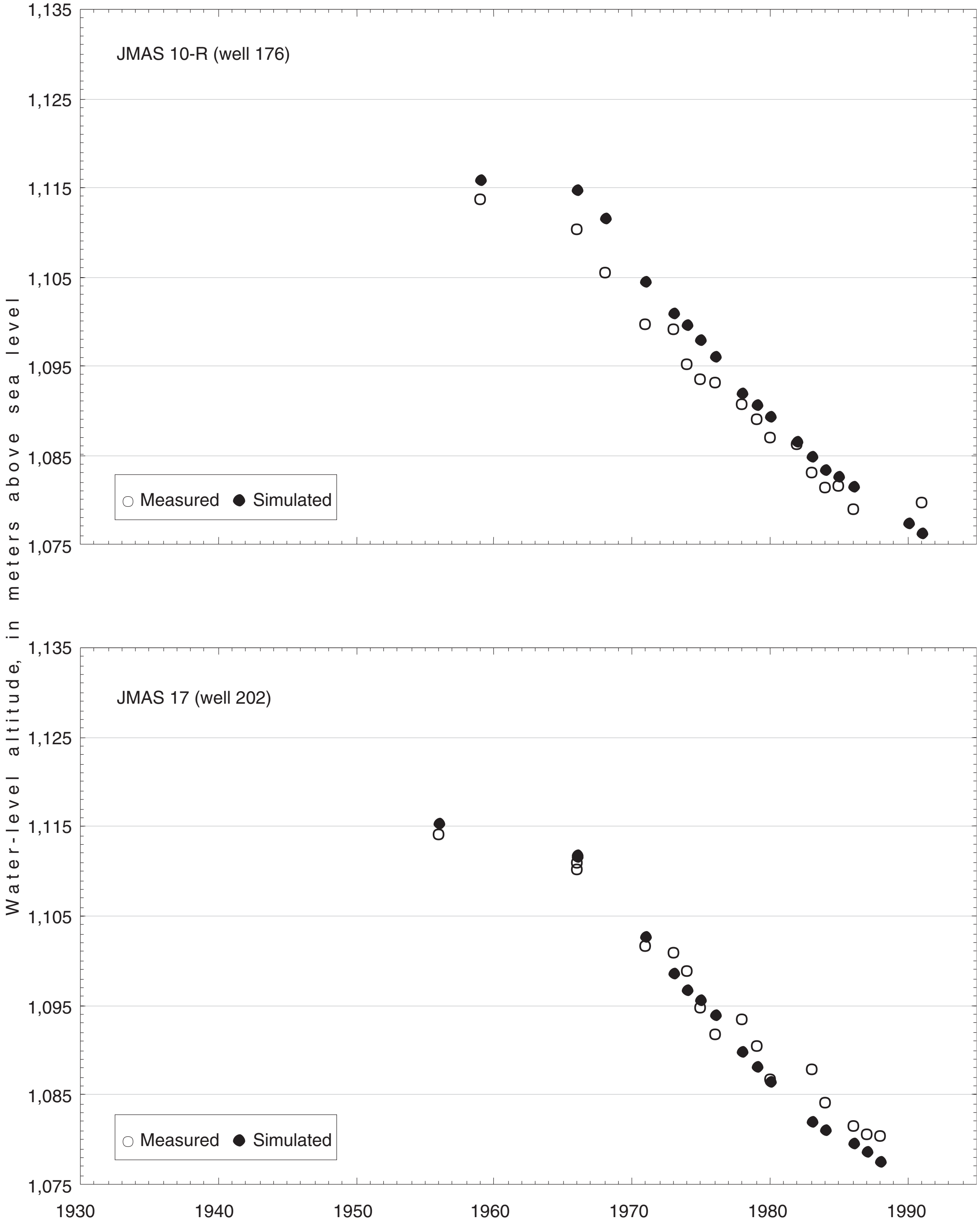


Figure 17E. Measured and simulated water levels from 1930 through 1995 in selected wells in the Juarez well field (location of wells shown in figure 11).

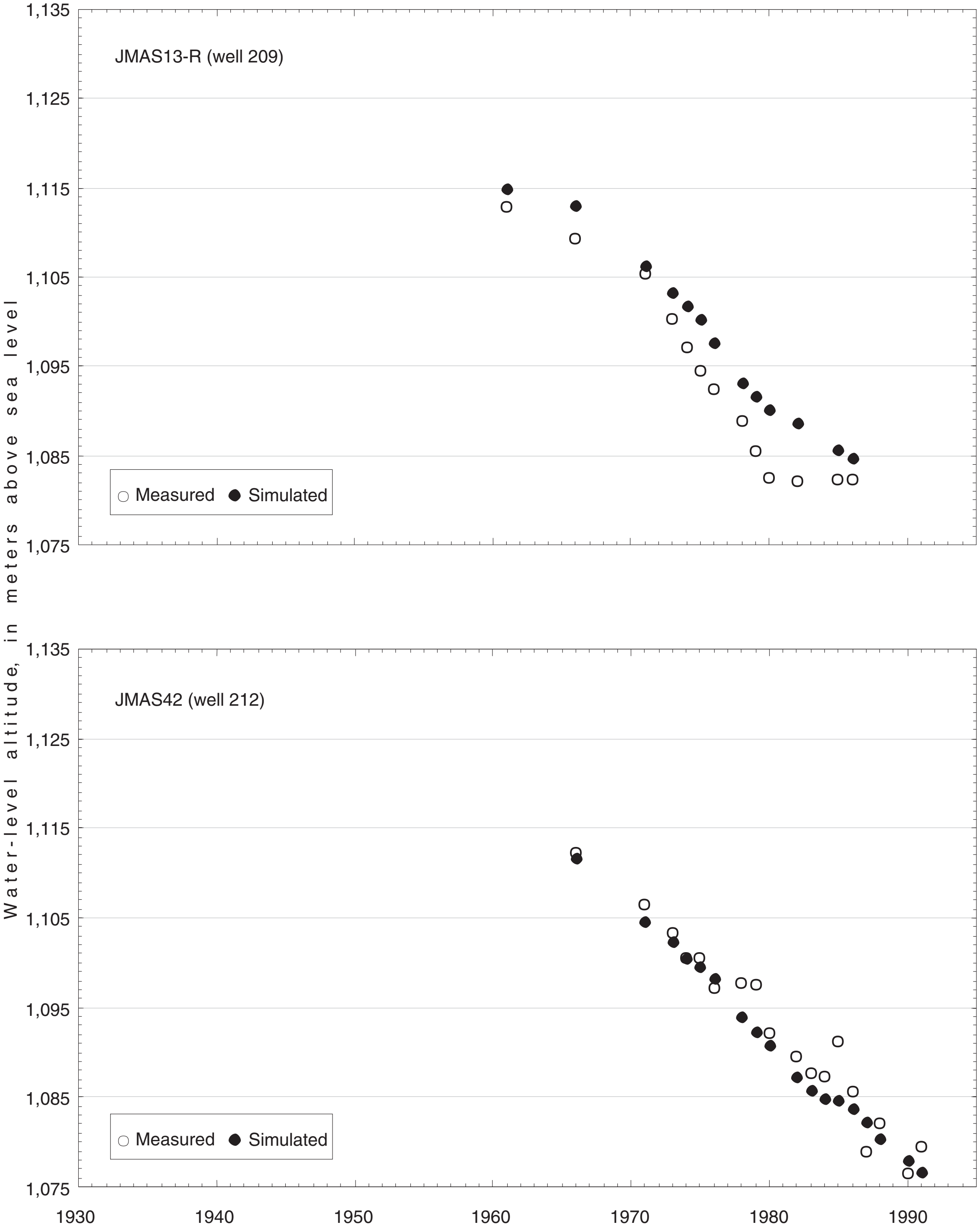


Figure 17E. Measured and simulated water levels from 1930 through 1995 in selected wells in the Juarez well field (location of wells shown in figure 11)--Concluded.

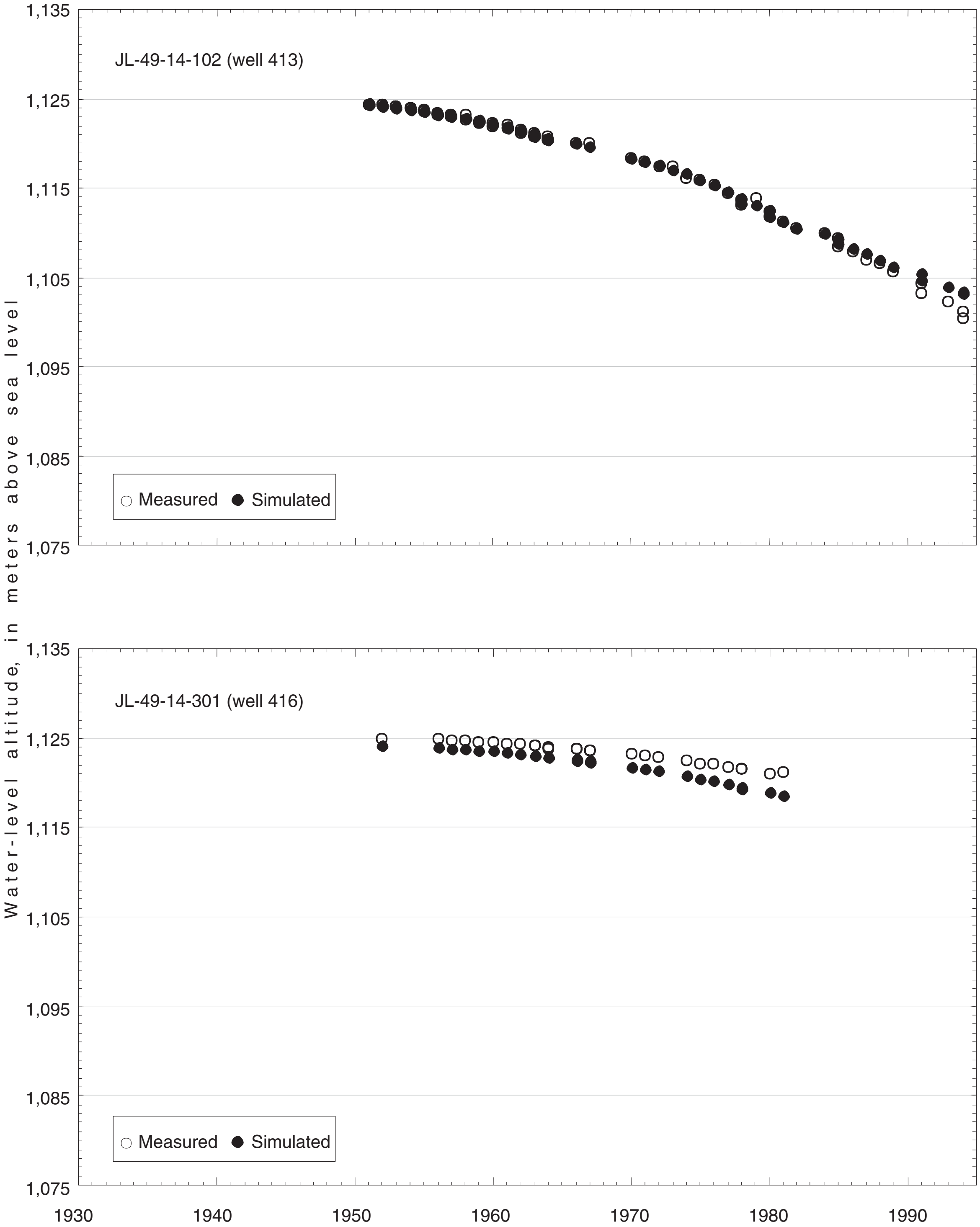


Figure 17F. Measured and simulated water levels from 1930 through 1995 in selected wells in the east observation well field (location of wells shown in figure 11).

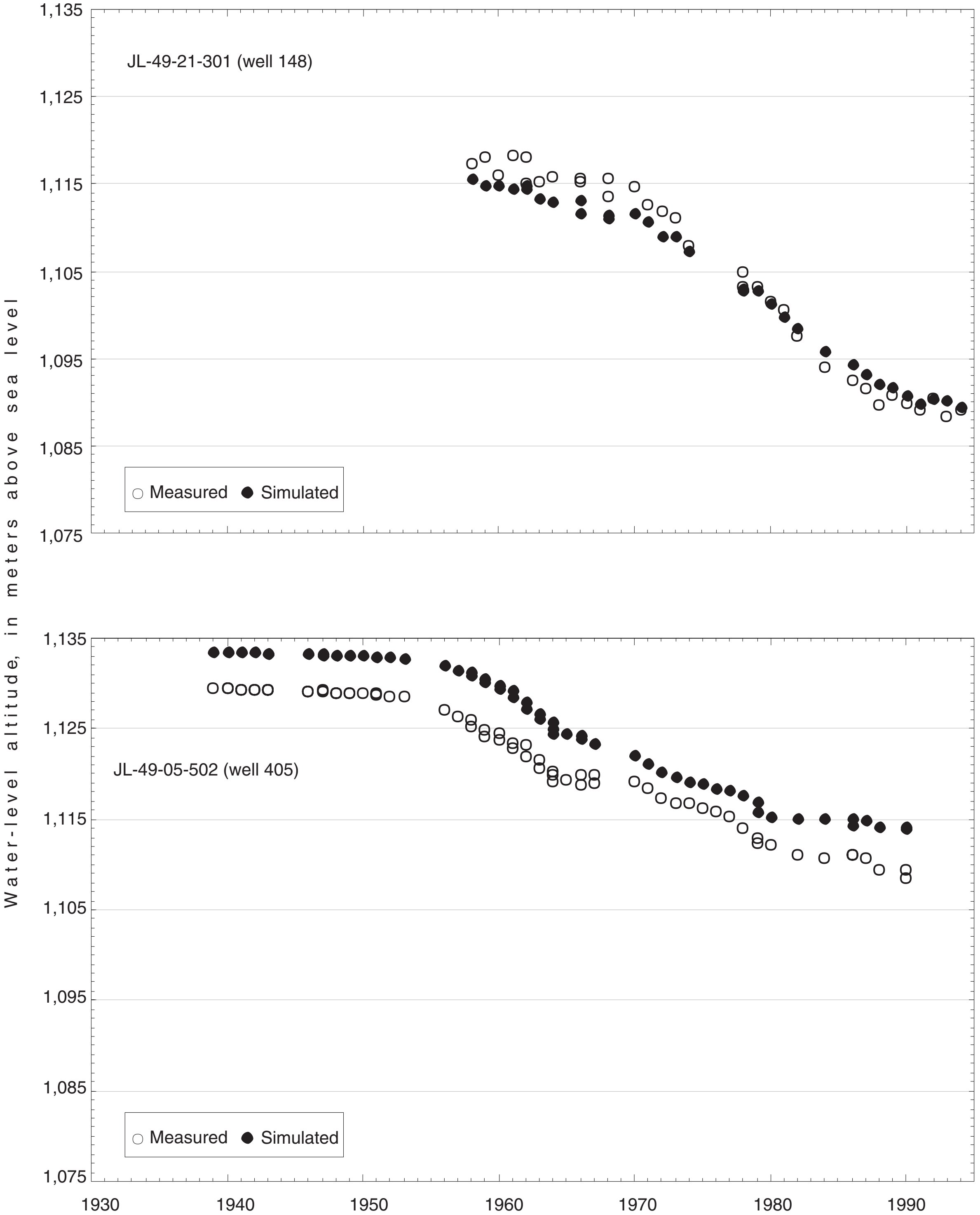


Figure 17G. Measured and simulated water levels from 1930 through 1995 in selected wells in the lower valley and north observation well fields (location of wells shown in figure 11).

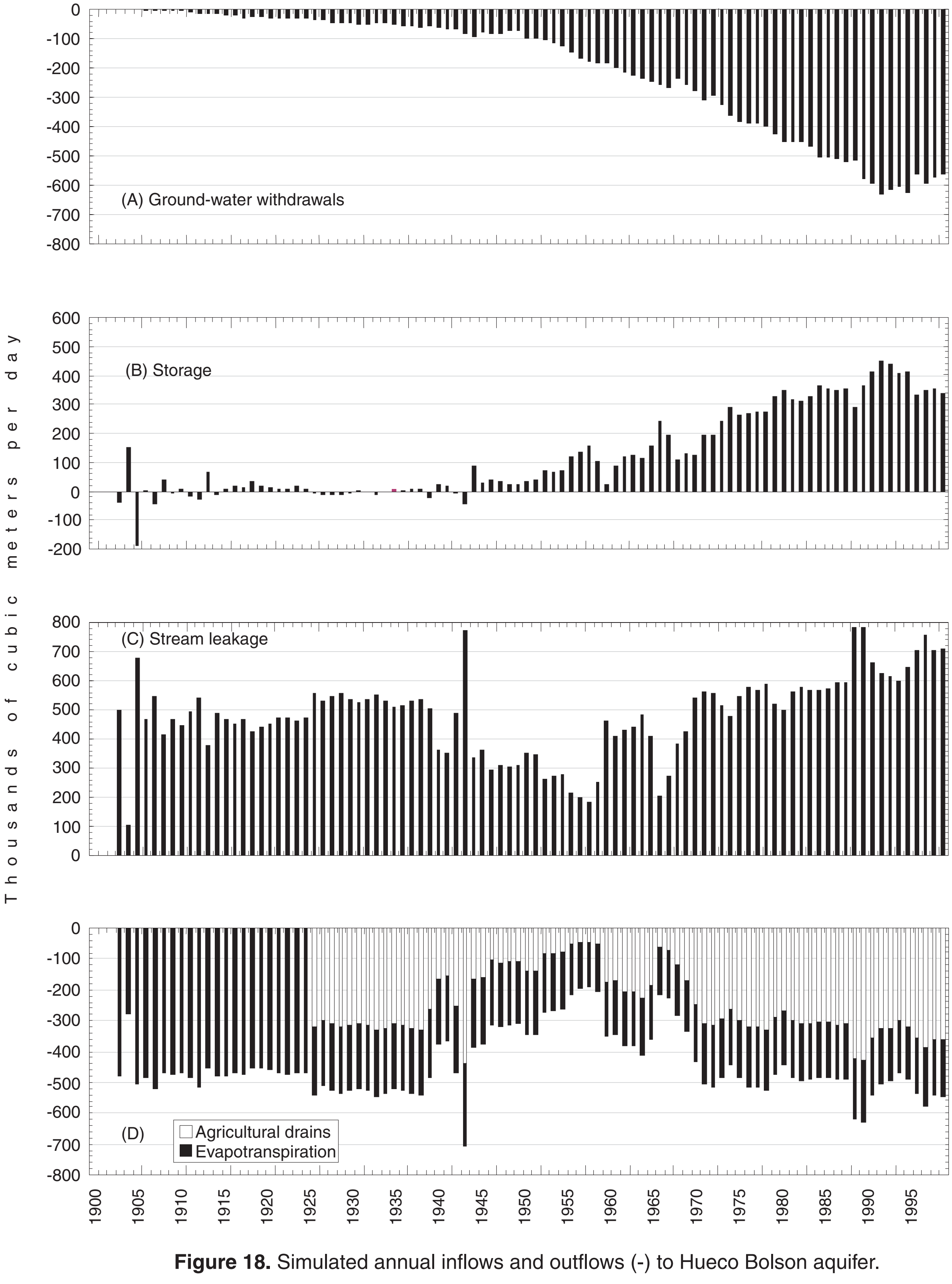


Figure 18. Simulated annual inflows and outflows (-) to Hueco Bolson aquifer.

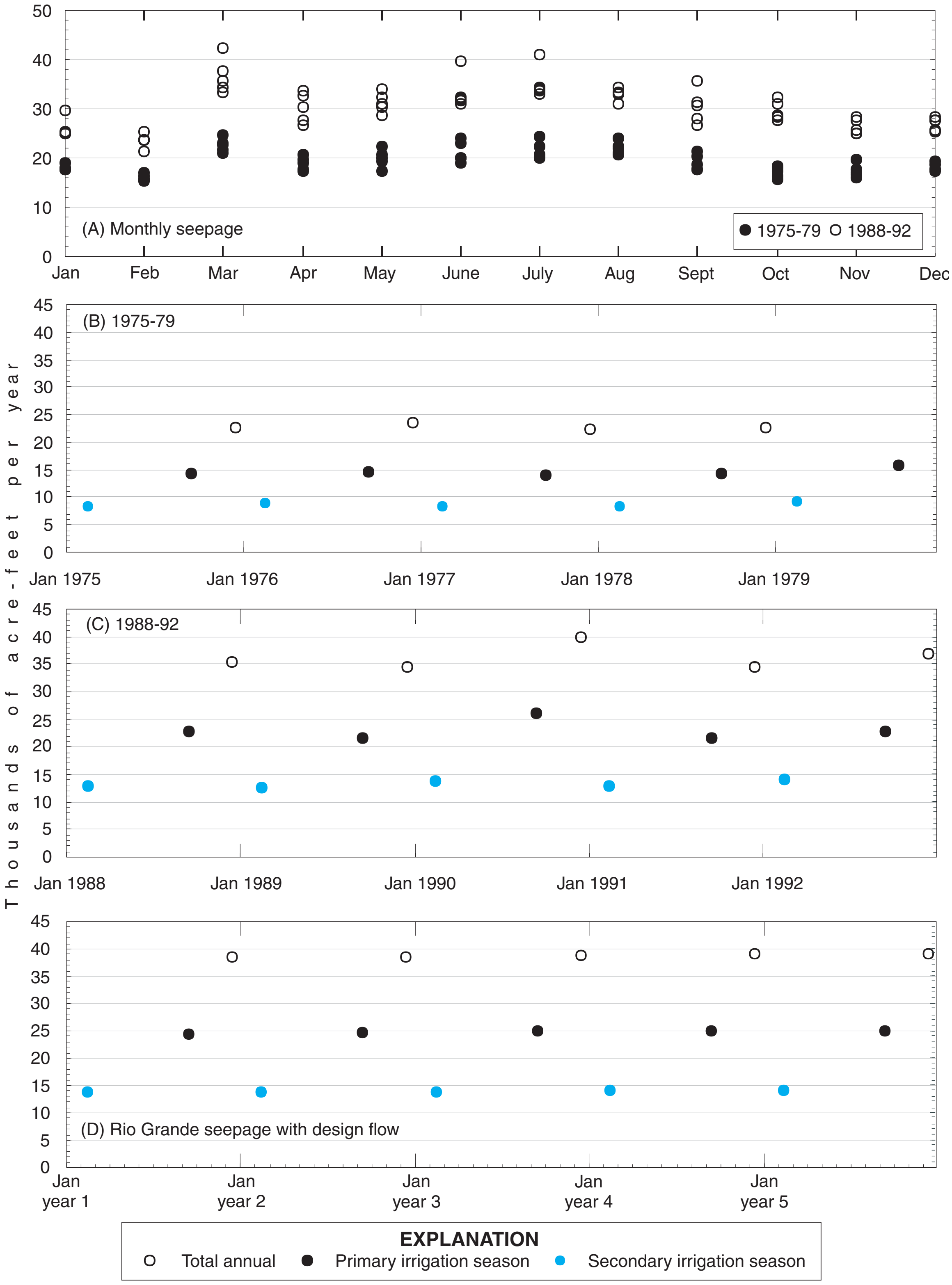


Figure 19. Rio Grande seepage between Chamizal zone and Riverside Dam (locations shown in figure 8).

The simulated seepage for the 10th year of a "design flow" in the Rio Grande without the ACE is illustrated in figure 10D. This design-flow seepage-loss calculation is for a hypothetical scenario in which Rio Grande water is not diverted into the ACE. The simulated aquifer conditions for this scenario approximate those that would have occurred during 2002 if the monthly ground-water pumpage rates and patterns in 1992 repeated for 10 years. The computed seepage loss from the Rio Grande to the underlying aquifer along the 15-km reach between the end of the Chamizal zone and Riverside Dam is 39,000 acre-ft/yr in this scenario.

The altitudes of drain beds specified in the model influence simulated water-table altitudes in portions of the Rio Grande Valley, which could affect seepage rates from the Rio Grande to the underlying aquifer. Although uncertainty exists for the drain-bed altitudes specified in the simulation (which are probably +1, -2 m), these altitudes were not formally estimated during the model-calibration process. To test the possible Rio Grande seepage-loss effect of the specified drain-bed altitudes, several forward model runs were made with drain-bed altitudes decreased in increments of 1 m. Although drain seepage increased, seepage loss from the Rio Grande between the end of the Chamizal zone and Riverside Dam remained at 39,000 acre-ft/yr. Within the tested drain-bed altitude range, which brackets values deemed reasonable, seepage loss from this reach of the Rio Grande is insensitive to specified drain-bed altitude.

The calibration on both the computed Rio Grande seepage losses and the adjustments to measured flow required for stream-package flow specification (see "Streamflow routing" section) was further checked by comparing evaporation-corrected, model-simulated flow at Riverside Dam with measured flow (computed as the sum of measured flow in the Riverside Canal and measured flow at Coffer Dam). These computations are shown in figure 20 for 1988-92. In general, the model fit is excellent, with the exception of 1990. Of the 348 monthly stress periods not shown in this figure, 346 had an excellent fit comparable with those of 1988-89 and 1991-92. The 2 years with months of substandard fit were 1975 and 1986. The years of substandard fit may have resulted from Rio Grande flow-measurement errors.

SUMMARY AND CONCLUSIONS

The neighboring cities of El Paso, Texas, and Ciudad Juarez, Chihuahua, Mexico, have historically relied on ground-water withdrawals from the Hueco Bolson, an alluvial-aquifer system, to supply water to their growing populations. In the United States, diversions from the Rio Grande and ground-water withdrawals from the Mesilla Basin west of the study area also supply the freshwater demands of the military, industries, and public in the El Paso area. In Mexico, diversions from the Rio Grande are used for agriculture; water needed by Ciudad Juarez is supplied solely by extraction from the Hueco Bolson. By 1996, ground-water drawdown exceeded 60 m in some areas under Ciudad Juarez and El Paso. Fresh ground water stored in the aquifer system beneath these cities is bordered by regions of brackish to saline ground water. As water levels in the freshwater portions of the aquifer declined, intrusion of the surrounding brackish water degraded water quality in public supply wells, which sometimes required well abandonment.

By the end of 1996, ground-water levels had declined by as much as 60 m (197 ft) from simulated steady-state levels in the Hueco Bolson. By incorporating extensive pumpage records with fine spatial and temporal discretization, these declines have been simulated in a numerical ground-water flow model that matches 4,352 head observations with an SEE of about 3 m. This monthly temporal discretization was needed to (1) permit accurate calculations of seepage losses from the Rio Grande and (2) provide a useful ground-water management model.

The simulation of steady-state and transient ground-water flow in the Hueco Bolson was developed using MODFLOW-96. The transient simulation represents a period of 100 years beginning in 1903 and ending in 2002. The period 1903 through 1968 was represented with 66 annual stress periods, and the period 1969 through 2002 was represented with 408 monthly stress periods. Model boundary conditions were modified at appropriate times during the simulation to represent changes in well pumpage, drainage of agricultural fields, and channel modifications of the Rio Grande.

The model was calibrated using MODFLOWP and UCODE. Parameter values representing aquifer properties and boundary conditions were adjusted through nonlinear regression in a transient-state simulation with 96 annual time steps to produce a model that approximated (1) 4,352 water levels

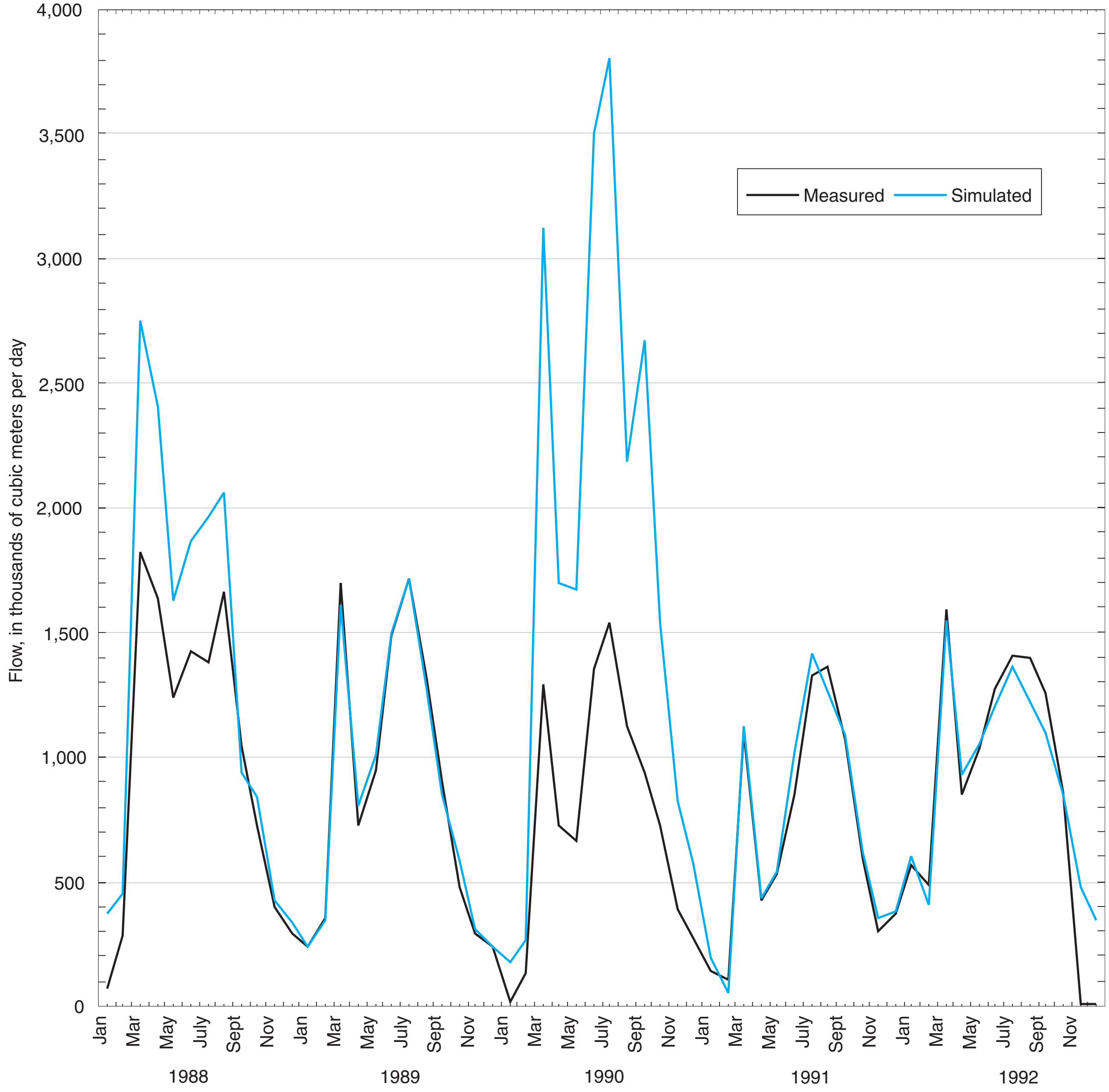


Figure 20. Simulated and measured flows at Riverside Dam (location shown in figure 8).

measured in 292 wells from 1912 to 1995, (2) three seepage-loss rates from a reach of the Rio Grande during periods from 1979 to 1981, (3) three seepage-loss rates from a reach of the Franklin Canal during periods from 1990 to 1992, and (4) 24 seepage rates into irrigation drains from 1961 to 1983. Once a calibrated model was obtained with MODFLOWP and UCODE, the optimal parameter set was used to create an equivalent MODFLOW-96 simulation with monthly temporal discretization to improve computations of seepage from the Rio Grande and to define the flow field for a chloride-transport simulation.

The optimal values for a set of 17 parameters were obtained using nonlinear regression. Values of other parameters that were either well constrained or insensitive to the model were specified. The regression was constrained by the head and flow-loss measurements from the Rio Grande and Franklin Canal and flow observations in agricultural drains. The model was most sensitive to (1) horizontal hydraulic conductivity of the fluvial facies, which composes the principal aquifer material in which production wells are drilled, (2) specific yield, (3) recharge underflow from the Tularosa Basin, and (4) hydraulic conductance of Quaternary fault zones. Parameter distribution was generated from a simplified hydrogeologic model. Several more complex geologic conceptualizations, such as a dipping boundary between fluvial and lacustrine-playa facies, were parameterized and optimized as regression runs. These alternative models, though probably more geologically realistic, did not provide an overall improved fit to the hydraulic-head measurements. Future geologic refinements incorporated into the flow model may improve model fit in certain areas, however. Seepage losses for the 15-km reach of the Rio Grande channel between the Chamizal zone and Riverside Dam were computed with monthly stress periods. The seepage loss from the Rio Grande for a hypothetical "design flow” in the Rio Grande was 39,000 acre-ft/yr and was not sensitive to specified drain-bed altitudes within a reasonable range.

The model input was generated from GIS databases, which facilitated rapid model construction and enabled testing of several conceptualizations of hydrogeologic facies boundaries. The simulation results were sensitive to the hydraulic conductance of Quaternary faults in the fluvial-aquifer facies, suggesting that ground-water flow is impeded across the fault planes.

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APPENDIX 1: MODIFICATIONS TO MODFLOWP

Changes made to modflowp.f for all modifications

```
    DATA CUNIT/'BCF ', 'WEL ', 'DRN ', 'RIV ', 'EVT ', 'TLK ', 'GHB ',
   &     'RCH ', 'SIP ', 'DE4 ', 'SOR ', 'OC ', 'PCG ', 'GFD ',
   &     'PAR ', 'HFB ', 'RES ', 'STR ', 'IBS ', 'CHD ', 'MAW ',
   &     '    ', '    ', '    ', '    ', '    ', '    ', '    ',
   &     '    ', '    ', '    ', '    ', '    ', '    ', '    ',
   &     '    ', '    ', '    ', '    ', '    '/
```

... skip lines...

```
     IF (IUNIT(2).GT.0) CALL WEL5AL(ISUM,LENX,LCWELL,MXWELL,NWELLS,
   &                          IUNIT(2),IOUT,IWELCB,NWELVL,IWELAL,
   &                          IFREFM)
     IF(IUNIT(21).GT.0) CALL MAW5AL(ISUM,LENX,MXMAW,NMAWS,
   1   IUNIT(21),IOUT,NLAY,LCRMAW,LCRMAL,IMAWCB)
```

... skip lines...

```
     IF (IUNIT(18).GT.0) CALL STR5AL(ISUM,LENX,LCSTRM,ICSTRM,MXSTRM,
   &                           NSTREM,IUNIT(18),IOUT,ISTCB1,
   &                           ISTCB2,NSS,NTRIB,NDIV,ICALC,CONST,
   &                          LCTBAR,LCTRIB,LCIVAR,LCFGAR,NSTROP)
```

... skip lines...

```
        IF (IUNIT(2).GT.0) CALL WEL5RP(X(LCWELL),NWELLS,MXWELL,
   &                             IUNIT(2),IOUT,NWELVL,IWELAL,
   &                             IFREFM)
     IF(IUNIT(21).GT.0) CALL MAW5RP(X(LCRMAW),
   1   X(LCRMAL),NMAWS,MXMAW,IUNIT(21),IOUT,NLAY)
```

... skip lines...

```
        IF (IUNIT(2).GT.0) CALL WEL5FM(NWELLS,MXWELL,X(LCRHS),
   &                             X(LCWELL),X(LCIBOU),NCOL,
   &                             NROW,NLAY,NWELVL)
     IF(IUNIT(21).GT.0) CALL MAW5FM(NMAWS,MXMAW,X(LCRHS),X(LCHCOF),
   1   X(LCIBOU),X(LCRMAW),X(LCRMAL),NCOL,NROW,
   2   NLAY,X(LCCR),X(LCDELC),X(LCDELR),X(LCHNEW),IOUT)
```

... skip lines...

```
        IF (IUNIT(18).GT.0) CALL STR5FM(NSTREM,X(LCSTRM),X(ICSTRM),
   &                              X(LCHNEW),X(LCHCOF),X(LCRHS)
   &                         ,X(LCIBOU),MXSTRM,NCOL,NROW,
   &                              NLAY,IOUT,NSS,X(LCTBAR),
   &                              NTRIB,X(LCTRIB),X(LCIVAR),
   &                             X(LCFGAR),ICALC,CONST,NSTROP,
   &                              X(LCSHNW),IUNIT(15),IP,ISN)
```

... skip lines...

```
        IF (IUNIT(2).GT.0) CALL WEL5BD(NWELLS,MXWELL,VBNM,VBVL,MSUM,
   &                             X(LCWELL),X(LCIBOU),DELT,
   &                             NCOL,NROW,NLAY,KKSTP,KKPER,
   &                             IWELCB,ICBCFL,X(LCBUFF),IOUT,
   &                             PERTIM,TOTIM,NWELVL,IWELAL)
     IF(IUNIT(21).GT.0) CALL MAW5BD(NMAWS,MXMAW,X(LCIBOU),X(LCRMAW),
   1       X(LCRMAL),NCOL,NROW,NLAY,X(LCHNEW),KSTP,
   2   KPER,IMAWCB,ICBCFL,X(LCBUFF),IOUT,MSUM,DELT,VBNM,VBVL)
```

... skip lines...

```
      IF (IUNIT(18).GT.0) CALL STR5BD(NSTREM,X(LCSTRM),X(ICSTRM),
     &                       X(LCIBOU),MXSTRM,X(LCHNEW),
     &                       NCOL,NROW,NLAY,DELT,VBVL,
     &                       VBNM,MSUM,KKSTP,KKPER,
     &                       ISTCB1,ISTCB2,ICBCFL,
     &                       X(LCBUFF),IOUT,NTRIB,NSS,
     &                       X(LCTRIB),X(LCTBAR),
     &                       X(LCIVAR),X(LCFGAR),ICALC,
     &                       CONST,IPTFLG,NSTROP)
```

... skip lines...

```
      CALL SEN1OT(IUHEAD,IOUT,NROW,NCOL,NLAY,NP,ISN,NH,X(LCNDER),
     &    X(LCHNEW),PID,DID,IP,KPER,X(LCBUFF),KSTP,PERTIM,TOTIM,
     &    X(LCX),X(LCDELR),X(LCDELC),X(LCIBOU),X(LCCOFF),
     &    X(LCROFF),X(LCH),X(LCWT),X(LCHOBS),IPRINT,IFO,ITERP,
     &    IPAR,X(LCRINT),X(LCJOFF),X(LCIOFF),X(LCMLAY),X(LCPR),
     &    MOBS,NPER,X(LCB),X(LCLN),NQ,NQC,NQT,X(LCNQOB),
     &    X(LCNQCL),X(LCIQOB),X(LCQCLS),X(LCIBT),MXBND,NBOUND,
     &    X(LCBNDS),MXRIVR,NRIVER,X(LCRIVR),X(LCSHNW),LASTX,
     &    ISCALS,X(LCTOFF),MXDRN,NDRAIN,X(LCDRAI),MXSTRM,NSTREM,
     &    X(LCSTRM),X(ICSTRM),MAXM,KPRINT,JDRY,IDRY,NPR,X(LCWP),
     &    MPR,X(LCPRM),X(LCIWPG),X(LCB1),IOUB,RSQ,RSQP,RSQO,
     &    RSQOO,NPO,SOSC,SOSR,IPR,X(LCNIPR),X(LCWPF),ND,RSQF,
     &    IOUYR,IOUHDS,IOUFLW,IOUPRI,IUNORM,X(LCWTQ),X(LCWTQS),
     &    IOWTQ,NDMH,X(LCPV),X(LCRHS),X(LCCR),X(LCCC),X(LCCV),
     &    X(LCBOT),X(LCTOP),NPTH,X(LCNPNT),NTT2,KTDIM,KTREV,
     &    X(LCICLS),X(LCPRST),X(LCPOFF),X(LCSMAT),X(LCNLL),NSM,
     &    X(LCTRPY),NMM,NZM,LZI1,X(LCSFAC),X(LCLZ),X(LCLM),
     &    X(LCMATZ),NLLI1,X(LCST),X(LCTT2),IOUTT2,NRCHOP,
     &    X(LCIRCH),X(LCRECH),X(LCSV),X(LCBANI),X(LCTHCK),NCLAY,
     &    KTFLG,ADVSTP,X(LCLAYC),NSTROP)
```

Compute heads for multi-layer observations with dry cells: ssen1jz.f

Subroutine SSEN1U

This subroutine interpolates heads and accounts for dry cells, if necessary.

```
    REAL B, COFF, DELC, DELR, FACT, H, HD, HOBS, PR, PROP, RHS, RINT,
  &    ROFF, TOFF, W, WT, X, ZERO, PROLD
```

...skip lines...

```
C---------IF THE OBSERVATION THIS IS TO BE SUBTRACTED FROM IS DRY, MAKE
C---------THIS ONE DRY, TOO
      N1 = NDER(5,N)
      IF (N1.GT.0) THEN
        IF ((WT(N1).LT.ZERO.OR.COFF(N1).GE.5.)) THEN
          IDRY = IDRY + 1
          WT(N) = -ABS(WT(N))
          WRITE (IOUT,500) N, DID(N)
          GOTO 30
        ENDIF
      ENDIF
C---------CHECK FOR DRY OBSERVATIONS OR INTERPOLATIONS AFFECTED BY DRY
C---------CELLS
      DO 20 M = 1, MM
        KK = K
        IF (K.LT.0) KK = MLAY(M,ML)
        IF (KK.EQ.0) GOTO 30
        IF (LAYCON(KK).EQ.1 .OR. LAYCON(KK).EQ.3) THEN
          IF (IBOUND(JJ,II,KK).EQ.0) THEN
C***      dry cell in observation stack:
C***      more than 1 layer in observations
C***      change MLAY (move layer definitions forward in array)
C***     recalculate pr
C***      at least 1 non dry layer?
C***      goto 20
            IF (MLAY(M+1,ML).eq.0) GOTO 13
              PROLD = PR(M,ML)
              DO 11 MTMP = M, MM-1
                IF (MLAY(MTMP,ML).eq.0) GOTO 12
                MLAY(MTMP,ML) = MLAY(MTMP+1,ML)
                PR(MTMP,ML) = PR(MTMP+1,ML)/(1-PROLD)
                IF (PR(MTMP+1,ML).eq.0) PR(MTMP,ML) = 0
   11           CONTINUE
              MLAY(MM,ML) = 0
              PR(MM,ML) = 0
   12           IF (MLAY(1,ML).gt.0) GOTO 20
   13           IDRY = IDRY + 1
              WT(N) = -ABS(WT(N))
              WRITE (IOUT,500) N, DID(N)
              GOTO 30
          ELSEIF ((RINT(2,N).NE.ZERO.AND.IBOUND(JJ+JO,II,KK)
     &           .EQ.0) .OR.
     &            (RINT(3,N).NE.ZERO.AND.IBOUND(JJ,II+IO,KK)
     &            .EQ.0) .OR.
     &            (RINT(4,N).NE.ZERO.AND.IBOUND(JJ+JO,II+IO,KK)
     &            .EQ.0)) THEN
C***      dry cell in adjacent stack:
C***              IF (MM.GT.1 .OR. TOFF(N).GT.ZERO) THEN
C***      multi-layer observation
              IF (MM.GT.1) THEN
C***      adjust PR and ML arrays as above
               IF (MLAY(M+1,ML).eq.0) GOTO 16
                PROLD = PR(M,ML)
                DO 14 MTMP = M, MM-1
```

```
                IF (MLAY(MTMP,ML).eq.0) GOTO 15
                MLAY(MTMP,ML) = MLAY(MTMP+1,ML)
                PR(MTMP,ML) = PR(MTMP+1,ML)/(1-PROLD)
                IF (PR(MTMP+1,ML).eq.0) PR(MTMP,ML) = 0
 14             CONTINUE
               MLAY(MM,ML) = 0
               PR(MM,ML) = 0
 15             IF (MLAY(1,ML).gt.0) GOTO 20
              ENDIF
 16            IF (MM.GT.1 .OR. TOFF(N).GT.ZERO) THEN
               IDRY = IDRY + 1
               WT(N) = -ABS(WT(N))
               WRITE (IOUT,500) N, DID(N)
               GOTO 30
              ENDIF
```

Compute leakage from streams to underlying active cells: str5p.f

Subroutine STR5AL

This subroutine allocates array storage for streams.

```
      SUBROUTINE STR5AL(ISUM,LENX,LCSTRM,ICSTRM,MXSTRM,NSTREM,IN,IOUT,
     &           ISTCB1,ISTCB2,NSS,NTRIB,NDIV,ICALC,CONST,LCTBAR,
     &           LCTRIB,LCIVAR,LCFGAR,NSTROP)
```

... skip lines...

```
       READ (IN,505) MXSTRM, NSS, NTRIB, NDIV, ICALC, CONST, ISTCB1,
     &         ISTCB2,NSTROP
 505 FORMAT (5I10,F10.0,3I10)
```

... skip lines...

```
  540 FORMAT ('    ***X ARRAY MUST BE DIMENSIONED LARGER***')
C
C3------CHECK TO SEE THAT OPTION IS LEGAL.
      IF(NSTROP.GE.1.AND.NSTROP.LE.3) GO TO 560
C
C3A-----IF ILLEGAL PRINT A MESSAGE AND ABORT SIMULATION
      WRITE(IOUT,550)
 550 FORMAT(1X,'ILLEGAL OPTION CODE. SIMULATION ABORTING')
      STOP
C
C4------PRINT OPTION CODE.
  560 IF(NSTROP.EQ.1) WRITE(IOUT,565)
  565 FORMAT(1X,'OPTION 1 -- LEAKAGE TO DEFINED LAYER')
      IF(NSTROP.EQ.3) WRITE(IOUT,570)
  570 FORMAT(1X,'OPTION 3 -- LEAKAGE TO HIGHEST ACTIVE NODE IN EACH',
     1       ' VERTICAL COLUMN')
C
C10-----RETURN.
       RETURN
       END
```

Subroutine STR5FM

This subroutine adds stream terms to RHS and HCOF if flow occurs in model cell.

```
      SUBROUTINE STR5FM(NSTREM,STRM,ISTRM,HNEW,HCOF,RHS,IBOUND,MXSTRM,
     &           NCOL,NROW,NLAY,IOUT,NSS,ITRBAR,NTRIB,ARTRIB,
     &          IDIVAR,NDFGAR,ICALC,CONST,NSTROP,SHNW,IU,IP,ISN)
```

... skip lines ...

```
C12----DETERMINE LEAKAGE THROUGH STREAMBED.
C      IF DRY CELL AND OPTION 3, CHECK FOR HIGHEST ACTIVE CELL
        IF ((IBOUND(IC,IR,IL).LT.1).AND.(NSTROP.EQ.1)) THEN
          FLOBOT = ZERO
         ELSE
         IF((IBOUND(IC,IR,IL).LE.0).AND.(NSTROP.EQ.3)) THEN
C12A------IF OPTION IS 3 LEAKAGE IS INTO HIGHEST INTERNAL CELL.
C        CANNOT PASS THROUGH CONSTANT HEAD NODE
           DO 42 NIL=IL+1,NLAY
C
C12B-----IF CELL IS: CONSTANT HEAD MOVE ON TO NEXT STREAM REACH
C                   INACTIVE MOVE DOWN A LAYER
C                   ACTIVE SET LEAKAGE TO CONSTANT
           IF(IBOUND(IC,IR,NIL)) 43,42,44
   42        CONTINUE
C--------NO ACTIVE CELLS FOUND, NO LEAKAGE
   43        FLOBOT=0.
           GO TO 45
         ENDIF
   44    IF (FLOWIN.LE.ZERO) HSTR = STRM(5,L)
         CSTR = STRM(3,L)
         SBOT = STRM(4,L)
         H = HNEW(IC,IR,IL)
C***   set head to top active layer if dry cell
         IF(IBOUND(IC,IR,IL).EQ.0) H=HNEW(IC,IR,NIL)
C-----ADDED FOR PARAMETER ESTIMATION
         IF (IU.GT.0 .AND. IP.NE.0) H = SHNW(IC,IR,IL)
         IF(IU.GT.0.AND.IP.NE.0.AND.IBOUND(IC,IR,IL).EQ.0)
     +     H=SHNW(IC,IR,NIL)
```

... skip lines...

```
C16-----STREAMFLOW OUT EQUALS STREAMFLOW IN MINUS LEAKAGE.
           IF ((IBOUND(IC,IR,IL).LT.1).AND.(NSTROP.EQ.1)) FLOBOT = ZERO
            ENDIF
          ENDIF
   45   FLOWOT = FLOWIN - FLOBOT
          IF (ISTSG.GT.1 .AND. NREACH.EQ.1) STRM(9,LL) = ARTRIB(IFLG)
C
C17----STORE STREAM INFLOW, OUTFLOW AND LEAKAGE FOR EACH REACH.
          STRM(9,L) = FLOWOT
          STRM(10,L) = FLOWIN
          STRM(11,L) = FLOBOT
C
C18----RETURN TO STEP 3 IF STREAM INFLOW IS LESS THAN OR EQUAL TO ZERO
C      AND LEAKAGE IS GREATER THAN OR EQUAL TO ZERO OR IF CELL
C      IS NOT ACTIVE--IBOUND IS LESS THAN OR EQUAL TO ZERO--
C      & NSTROP=1.
        IF ((IBOUND(IC,IR,IL).GT.0).OR.(NSTROP.EQ.3)) THEN
C***   reset top active layer if dry cell
         IF(IBOUND(IC,IR,IL).EQ.0) IL=NIL
            IF (FLOWIN.GT.ZERO .OR. FLOBOT.LT.ZERO) THEN
C
C19------IF HEAD > BOTTOM THEN ADD TERMS TO RHS AND HCOF.
           IF (IQFLG.LT.1) THEN
C--------FOR ADJOINT STATES, ONLY CALCULATE CONTRIBUTION TO HCOF
            IF (IU.EQ.0 .OR. IP.EQ.0 .OR. ISN.LT.0)
     &          RHS(IC,IR,IL) = RHS(IC,IR,IL) - CSTR*HSTR
            HCOF(IC,IR,IL) = HCOF(IC,IR,IL) - CSTR
           ELSE
C
C20------IF HEAD < BOTTOM THEN ADD TERM ONLY TO RHS.
C-------FOR ADJOINT STATES, ONLY CALCULATE CONTRIBUTION TO HCOF
            IF (IU.EQ.0 .OR. IP.EQ.0 .OR. ISN.LT.0) THEN
             RHS(IC,IR,IL)=RHS(IC,IR,IL) - FLOBOT
```

```
            ENDIF
          ENDIF
        ENDIF
      ENDIF
   50 CONTINUE
```

Subroutine STR5BD

This subroutine calculates volumetric budget for streams.

```
      SUBROUTINE STR5BD(NSTREM,STRM,ISTRM,IBOUND,MXSTRM,HNEW,NCOL,NROW,
     &                  NLAY,DELT,VBVL,VBNM,MSUM,KSTP,KPER,ISTCB1,
     &                  ISTCB2,ICBCFL,BUFF,IOUT,NTRIB,NSS,ARTRIB,ITRBAR,
     &                  IDIVAR,NDFGAR,ICALC,CONST,IPTFLG,NSTROP)
```

... skip lines...

```
C14----DETERMINE LEAKAGE THROUGH STREAMBED.
          IF ((IBOUND(IC,IR,IL).LT.1).AND.(NSTROP.EQ.1)) THEN
            FLOBOT = ZERO
          ELSE
           IF((IBOUND(IC,IR,IL).LE.0).AND.(NSTROP.EQ.3)) THEN
             DO 72 NIL=IL+1,NLAY
C
C18A-----IF CELL IS: CONSTANT HEAD MOVE ON TO NEXT STREAM REACH
C                  INACTIVE MOVE DOWN A LAYER
C                  ACTIVE SET LEAKAGE TO CONSTANT
              IF(IBOUND(IC,IR,NIL)) 73,72,75
   72          CONTINUE
C--------NO ACTIVE CELLS FOUND, NO LEAKAGE
   73          FLOBOT=0.
             GO TO 77
   75        IF (STRM(3,L).ne.0)
     &           WRITE (IOUT,400) NIL, ISTRM(4,L), ISTRM(5,L), IR, IC
  400          FORMAT (/,5X,'LEAKAGE TO LAYER',I5,' FROM STREAM SEG',
     &              I6,' STREAM REACH',I6,' IN ROW',I5,' COLUMN',I5)
           ENDIF
           IF (FLOWIN.LE.ZERO) HSTR = STRM(5,L)
             CSTR = STRM(3,L)
           SBOT = STRM(4,L)
             H = HNEW(IC,IR,IL)
C***   set head to top active layer if dry cell
           IF(IBOUND(IC,IR,IL).EQ.0) H=HNEW(IC,IR,NIL)
```

... skip lines...

```
C18----STREAMFLOW OUT EQUALS STREAMFLOW IN MINUS LEAKAGE.
            IF ((IBOUND(IC,IR,IL).LT.1).AND.(NSTROP.EQ.1))
     &          FLOBOT = ZERO
           ENDIF
         ENDIF
   77    FLOWOT = FLOWIN - FLOBOT
         IF (ISTSG.GT.1 .AND. NREACH.EQ.1) STRM(9,LL) = ARTRIB(IFLG)
C
C19----STORE STREAM INFLOW, OUTFLOW AND LEAKAGE FOR EACH REACH.
         STRM(9,L) = FLOWOT
         STRM(10,L) = FLOWIN
         STRM(11,L) = FLOBOT
C
C20----IF LEAKAGE FROM STREAMS IS TO BE SAVED THEN ADD RATE TO BUFFER.
C------OPTION=3; LEAKAGE IS INTO HIGHEST CELL IN A VERTICAL COLUMN
C------THAT IS NOT NO FLOW. IF NO ACTIVE CELLS EXIST THEN ZERO STREAM
C------LEAKAGE
        IF ((IBD.EQ.1).AND.(FLOBOT.NE.0.0)) THEN
         IF(IBOUND(IC,IR,IL).GT.0) THEN
```

```
         BUFF(IC,IR,IL)=BUFF(IC,IR,IL) + FLOBOT
        ELSE
         BUFF(IC,IR,NIL)=BUFF(IC,IR,NIL) + FLOBOT
        ENDIF
      ENDIF
C
C21----DETERMINE IF FLOW IS INTO OR OUT OF MODEL CELL.
```

... skip lines...

```
C29-----SAVE STREAMFLOWS OUT OF EACH REACH ON DISK.
          DO 120 L = 1, NSTREM
             IC = ISTRM(3,L)
              IR = ISTRM(2,L)
              IL = ISTRM(1,L)
           IF (IBOUND(IC,IR,IL).GT.0)
    &        BUFF(IC,IR,IL) = BUFF(IC,IR,IL) + STRM(9,L)
C***   reset top active layer if dry cell
        IF ((IBOUND(IC,IR,IL).LE.0).AND.(NSTROP.EQ.3)) THEN
          DO 118 NIL=IL+1,NLAY
C
C29A-----IF CELL IS: CONSTANT HEAD MOVE ON TO NEXT STREAM REACH
C                   INACTIVE MOVE DOWN A LAYER
             IF(IBOUND(IC,IR,NIL)) 118,119,118
  118        CONTINUE
          GO TO 120
  119         BUFF(IC,IR,NIL) = BUFF(IC,IR,NIL) + STRM(9,L)
        ENDIF
   120  CONTINUE
          CALL UBUDSV(KSTP,KPER,STRTXT,ISTCB2,BUFF,NCOL,NROW,NLAY,IOUT)
```

Subroutine PAR1AQ

This subroutine calculates final iteration parameters and updates parameters.

```
      CALL SSEN1V(NQ,NQC,NQT,NQOB,NQCL,IQOB,QCLS,IBT,MXBND,NBOUND,
    &             BNDS,MXRIVR,NRIVER,RIVR,SHNW,IP,HNEW,NCOL,NROW,NLAY,
    &             IOUT,IBOUND,NPER,KPER,NH,X,DID,NP,H,B,LN,TOFF,
    &             MXDRN,NDRAIN,DRAI,MXSTRM,NSTREM,STRM,ISTRM,ISN,
    &             WTQ,NDMH,NSTROP)
```

Subroutine SEN1OT

This subroutine prints data for observed heads and flows.

```
      SUBROUTINE SEN1OT(IUHEAD,IOUT,NROW,NCOL,NLAY,NP,ISN,NH,NDER,HNEW,
    &                PID,DID,IP,KPER,BUFF,KSTP,PERTIM,TOTIM,X,DELR,
    &                DELC,IBOUND,COFF,ROFF,H,WT,HOBS,IPRINT,IFO,
    &                ITERP,IPAR,RINT,JOFF,IOFF,MLAY,PR,MOBS,NPER,B,
    &                LN,NQ,NQC,NQT,NQOB,NQCL,IQOB,QCLS,IBT,MXBND,
    &                NBOUND,BNDS,MXRIVR,NRIVER,RIVR,SHNW,LASTX,
    &                ISCALS,TOFF,MXDRN,NDRAIN,DRAI,MXSTRM,NSTREM,
    &                STRM,ISTRM,MAXM,KPRINT,JDRY,IDRY,NPR,WP,MPR,PRM,
    &                IWPG,B1,IOUB,RSQ,RSQP,RSQO,RSQOO,NPO,SOSC,SOSR,
    &                IPR,NIPR,WPF,ND,RSQF,IOUYR,IOUHDS,IOUFLW,IOUPRI,
    &                IUNORM,WTQ,WTQS,IOWTQ,NDMH,PV,RHS,CR,CC,CV,BOT,
    &                TOP,NPTH,NPNT,NTT2,KTDIM,KTREV,ICLS,PRST,POFF,
    &                SMAT,NLL,NSM,TRPY,NMM,NZM,LZI1,SFAC,LZ,LM,MATZ,
    &                NLLI1,ST,TT2,IOUTT2,NRCHOP,IRCH,RECH,SV,BANIV,
    &                THCK,NCLAY,KTFLG,ADVSTP,LAYC,NSTROP)
```

... skip lines...

```
       IF (NQ.GT.0) CALL SSEN1V(NQ,NQC,NQT,NQOB,NQCL,IQOB,QCLS,IBT,
```

```
     &                MXBND,NBOUND,BNDS,MXRIVR,NRIVER,RIVR,
     &                SHNW,IP,HNEW,NCOL,NROW,NLAY,IOUT,
     &                IBOUND,NPER,KPER,NH,X,DID,NP,H,B,LN,
     &                TOFF,MXDRN,NDRAIN,DRAI,MXSTRM,NSTREM,
     &                STRM,ISTRM,ISN,WTQ,NDMH,NSTROP)
```

Subroutine SSEN1V

This subroutine saves simulated flows and calculates sensitivities.

```
CHANGE 28.02.96:ARGUMENTS ADDED SUBROUTINE AND DIMENSION STATEMENT
   SUBROUTINE SSEN1V(NQ,NQC,NQT,NQOB,NQCL,IQOB,QCLS,IBT,MXBND,
    & NBOUND,BNDS,MXRIVR,NRIVER,RIVR,SHNW,IP,HNEW,NCOL,NROW,
     &           NLAY,IOUT,IBOUND,NPER,KPER,NH,X,DID,NP,H,B,LN,
     &           TOFF,MXDRN,NDRAIN,DRAI,MXSTRM,NSTREM,STRM,ISTRM,
     &           ISN,WTQ,NDMH,NSTROP)
```

... skip lines...

```
C-------------ASSIGN VARIABLE VALUES
            IF (IBT1.EQ.3) THEN
              K = ISTRM(1,NB)
              I = ISTRM(2,NB)
              J = ISTRM(3,NB)
C     IF DRY CELL AND OPTION 3, CHECK FOR HIGHEST ACTIVE CELL
              IF ((IBOUND(J,I,K).LT.1).AND.(NSTROP.EQ.1)) GOTO 30
              IF ((IBOUND(J,I,K).LE.0).AND.(NSTROP.EQ.3)) THEN
C------IF OPTION IS 3 LEAKAGE IS INTO HIGHEST INTERNAL CELL.
C       CANNOT PASS THROUGH CONSTANT HEAD NODE
                DO 5 NIL=K+1,NLAY
C
C-----IF CELL IS: CONSTANT HEAD MOVE ON TO NEXT STREAM REACH
C                INACTIVE MOVE DOWN A LAYER
C                ACTIVE SET LEAKAGE TO CONSTANT
                 IF(IBOUND(J,I,NIL)) 6,5,7
   5            CONTINUE
C--------NO ACTIVE CELLS FOUND, NO LEAKAGE
   6            GO TO 30
              ENDIF
            ENDIF
   7         IF (IP.EQ.0) HHNEW = HNEW(J,I,K)
            IF (IP.GT.0) HHNEW = SHNW(J,I,K)
```

APPENDIX 2: MODIFICATIONS TO MODFLOW

Changes made to modflw96.f for all modifications

```
      DATA CUNIT/'BCF ','WEL ','DRN ','RIV ','EVT ','TLK ','GHB ',
     1          'RCH ','SIP ','DE4 ','SOR ','OC  ','PCG ','GFD ',
     2          'MAW ','HFB ','RES ','STR ','IBS ','CHD ','FHB ',
     3          '    ','    ','    ','    ','    ','    ','    ',
     4          '    ','    ','    ','    ','    ','    ','    ',
     5          '    ','    ','    ','    ','    '/
```

... skip lines...

```
      IF(IUNIT(2).GT.0) CALL WEL5AL(ISUM,LENX,LCWELL,MXWELL,NWELLS,
     1             IUNIT(2),IOUT,IWELCB,NWELVL,IWELAL,IFREFM)
C***     multi-layer wells
      IF(IUNIT(15).GT.0) CALL MAW5AL(ISUM,LENX,MXMAW,NMAWS,
```

```
    1   IUNIT(15),IOUT,NLAY,LCRMAW,LCRMAL,IMAWCB)
```

... skip lines...

```
     IF(IUNIT(18).GT.0) CALL STR1AL(ISUM,LENX,LCSTRM,ICSTRM,MXSTRM,
    1               NSTREM,IUNIT(18),IOUT,ISTCB1,ISTCB2,NSS,NTRIB,
    2                NDIV,ICALC,CONST,LCTBAR,LCTRIB,LCIVAR,LCFGAR,
    3               NSTROP)
```

... skip lines...

```
     IF(IUNIT(2).GT.0) CALL WEL5RP(X(LCWELL),NWELLS,MXWELL,IUNIT(2),
    1          IOUT,NWELVL,IWELAL,IFREFM)
C***     multi-layer wells
     IF(IUNIT(15).GT.0) CALL MAW5RP(X(LCRMAW),
    1   X(LCRMAL),NMAWS,MXMAW,IUNIT(15),IOUT,NLAY)
```

... skip lines...

```
     IF(IUNIT(2).GT.0) CALL WEL5FM(NWELLS,MXWELL,X(LCRHS),X(LCWELL),
    1         X(LCIBOU),NCOL,NROW,NLAY,NWELVL)
C***     multi-layer wells
     IF(IUNIT(15).GT.0) CALL MAW5FM(NMAWS,MXMAW,X(LCRHS),X(LCHCOF),
    1   X(LCIBOU),X(LCRMAW),X(LCRMAL),NCOL,NROW,
    2   NLAY,X(LCCR),X(LCDELC),X(LCDELR),X(LCHNEW),IOUT)
```

... skip lines...

```
     IF(IUNIT(18).GT.0) CALL STR1FM(NSTREM,X(LCSTRM),X(ICSTRM),
    1                  X(LCHNEW),X(LCHCOF),X(LCRHS),X(LCIBOU),
    2             MXSTRM,NCOL,NROW,NLAY,IOUT,NSS,X(LCTBAR),
    3             NTRIB,X(LCTRIB),X(LCIVAR),X(LCFGAR),ICALC,CONST,
    4             NSTROP)
```

... skip lines...

```
      IF(IUNIT(2).GT.0) CALL WEL5BD(NWELLS,MXWELL,VBNM,VBVL,MSUM,
    1    X(LCWELL),X(LCIBOU),DELT,NCOL,NROW,NLAY,KKSTP,KKPER,IWELCB,
    1    ICBCFL,X(LCBUFF),IOUT,PERTIM,TOTIM,NWELVL,IWELAL)
C***     multi-layer wells
     IF(IUNIT(15).GT.0) CALL MAW5BD(NMAWS,MXMAW,X(LCIBOU),X(LCRMAW),
    1       X(LCRMAL),NCOL,NROW,NLAY,X(LCHNEW),KSTP,
    2   KPER,IMAWCB,ICBCFL,X(LCBUFF),IOUT,MSUM,DELT,VBNM,VBVL)
```

... skip lines...

```
     IF(IUNIT(18).GT.0) CALL STR1BD(NSTREM,X(LCSTRM),X(ICSTRM),       STR1
    1   X(LCIBOU),MXSTRM,X(LCHNEW),NCOL,NROW,NLAY,DELT,VBVL,VBNM,MSUM, STR1
    2   KKSTP,KKPER,ISTCB1,ISTCB2,ICBCFL,X(LCBUFF),IOUT,NTRIB,NSS,     STR1
    3   X(LCTRIB),X(LCTBAR),X(LCIVAR),X(LCFGAR),ICALC,CONST,IPTFLG,
    4   NSTROP)
```

Compute leakage from streams to underlying active cells: str1.f

Subroutine STR1AL

This subroutine allocates array storage for streams.

```
      SUBROUTINE STR1AL(ISUM,LENX,LCSTRM,ICSTRM,MXSTRM,NSTREM,IN,
     1               IOUT,ISTCB1,ISTCB2,NSS,NTRIB,NDIV,ICALC,CONST,
     2               LCTBAR,LCTRIB,LCIVAR,LCFGAR,NSTROP)
```

... skip lines...

```
C2------ READ MXSTRM, NSS, NTRIB, ISTCB1, AND ISTCB2.
  100 READ(IN,3)MXSTRM,NSS,NTRIB,NDIV,ICALC,CONST,ISTCB1,ISTCB2,NSTROP
```

```
      3 FORMAT(5I10,F10.0,3I10)

   ... skip lines...

   10 FORMAT(1X,'   ***X ARRAY MUST BE DIMENSIONED LARGER***')
C
C3------CHECK TO SEE THAT OPTION IS LEGAL.
      IF(NSTROP.GE.1.AND.NSTROP.LE.3) GO TO 250
C
C3A-----IF ILLEGAL PRINT A MESSAGE AND ABORT SIMULATION
      WRITE(IOUT,11)
   11 FORMAT(1X,'ILLEGAL OPTION CODE. SIMULATION ABORTING')
      STOP
C
C4------PRINT OPTION CODE.
  250 IF(NSTROP.EQ.1) WRITE(IOUT,12)
   12 FORMAT(1X,'OPTION 1 -- LEAKAGE TO DEFINED LAYER')
      IF(NSTROP.EQ.3) WRITE(IOUT,13)
   13 FORMAT(1X,'OPTION 3 -- LEAKAGE TO HIGHEST ACTIVE NODE IN EACH',
     1       ' VERTICAL COLUMN')

C10-----RETURN.
      RETURN
      END
```

Subroutine STR1FM

This subroutine adds stream terms to RHS and HCOF if flow occurs in model cell.

```
      SUBROUTINE STR1FM(NSTREM,STRM,ISTRM,HNEW,HCOF,RHS,IBOUND,MXSTRM,
     1                NCOL,NROW,NLAY,IOUT,NSS,ITRBAR,NTRIB,ARTRIB,
     2                IDIVAR,NDFGAR,ICALC,CONST,NSTROP)

... skip lines...

C12----DETERMINE LEAKAGE THROUGH STREAMBED.                          C
C     IF DRY CELL AND OPTION 3, CHECK FOR HIGHEST ACTIVE CELL
      IF((IBOUND(IC,IR,IL).LE.0).AND.(NSTROP.EQ.1)) GO TO 315
      IF((IBOUND(IC,IR,IL).LE.0).AND.(NSTROP.EQ.3)) THEN
C12A------IF OPTION IS 3 LEAKAGE IS INTO HIGHEST INTERNAL CELL.
C       CANNOT PASS THROUGH CONSTANT HEAD NODE
       DO 3101 NIL=IL+1,NLAY
C
C12B-----IF CELL IS: CONSTANT HEAD MOVE ON TO NEXT STREAM REACH
C                 INACTIVE MOVE DOWN A LAYER
C                 ACTIVE SET LEAKAGE TO CONSTANT
        IF(IBOUND(IC,IR,NIL)) 3102,3101,311
 3101    CONTINUE
C--------NO ACTIVE CELLS FOUND, NO LEAKAGE
 3102   FLOBOT=0.
         GO TO 320
         ENDIF
  311 IF(FLOWIN.LE.0.) HSTR=STRM(5,L)
        CSTR=STRM(3,L)
        SBOT=STRM(4,L)
        H=HNEW(IC,IR,IL)
C***   set head to top active layer if dry cell
      IF(IBOUND(IC,IR,IL).EQ.0) H=HNEW(IC,IR,NIL)
       T=HSTR-SBOT

... skip lines...

C16-----STREAMFLOW OUT EQUALS STREAMFLOW IN MINUS LEAKAGE.
  315 IF((IBOUND(IC,IR,IL).LE.0).AND.(NSTROP.EQ.1)) FLOBOT=0.
  320  FLOWOT=FLOWIN-FLOBOT
```

```
         IF((ISTSG.GT.1).AND.(NREACH.EQ.1)) STRM(9,LL)=ARTRIB(IFLG)
C
C17----STORE STREAM INFLOW, OUTFLOW AND LEAKAGE FOR EACH REACH.
         STRM(9,L)=FLOWOT
         STRM(10,L)=FLOWIN
         STRM(11,L)=FLOBOT
C
C18----RETURN TO STEP 3 IF STREAM INFLOW IS LESS THAN OR EQUAL TO ZERO
C      AND LEAKAGE IS GREATER THAN OR EQUAL TO ZERO, OR IF CELL
C      IS NOT ACTIVE--IBOUND IS LESS THAN OR EQUAL TO ZERO--
C      & NSTROP=1.
      IF((IBOUND(IC,IR,IL).LE.0).AND.(NSTROP.EQ.1)) GO TO 500
       IF((FLOWIN.LE.0.0).AND.(FLOBOT.GE.0.0)) GO TO 500
C
C19------IF HEAD > BOTTOM THEN ADD TERMS TO RHS AND HCOF.
C***   reset top active layer if dry cell
      IF(IBOUND(IC,IR,IL).EQ.0) IL=NIL
       IF(IQFLG.GT.0) GO TO 400
```

Subroutine STR1BD

This subroutine calculates volumetric budget for streams.

```
      SUBROUTINE STR1BD(NSTREM,STRM,ISTRM,IBOUND,MXSTRM,HNEW,NCOL,NROW,
     1  NLAY,DELT,VBVL,VBNM,MSUM,KSTP,KPER,ISTCB1,ISTCB2,ICBCFL,BUFF,
     2  IOUT,NTRIB,NSS,ARTRIB,ITRBAR,IDIVAR,NDFGAR,ICALC,CONST,IPTFLG,
     3  NSTROP)
```

... skip lines...

```
C14----DETERMINE LEAKAGE THROUGH STREAMBED.
        IF((IBOUND(IC,IR,IL).LE.0).AND.(NSTROP.EQ.1)) GO TO 315
        IF((IBOUND(IC,IR,IL).LE.0).AND.(NSTROP.EQ.3)) THEN
        DO 311 NIL=IL+1,NLAY
C
C18A-----IF CELL IS: CONSTANT HEAD MOVE ON TO NEXT STREAM REACH
C                 INACTIVE MOVE DOWN A LAYER
C                 ACTIVE SET LEAKAGE TO CONSTANT
         IF(IBOUND(IC,IR,NIL)) 3111,311,3112
   311   CONTINUE
C--------NO ACTIVE CELLS FOUND, NO LEAKAGE
 3111   FLOBOT=0.
         GO TO 320
 3112   IF (STRM(3,L).ne.0)
      &     WRITE (IOUT,900) NIL, ISTRM(4,L), ISTRM(5,L), IR, IC
  900   FORMAT (/,5X,'LEAKAGE TO LAYER',I5,' FROM STREAM SEG',
      &         I6,' STREAM REACH',I6,' IN ROW',I5,' COLUMN',I5)
         ENDIF
         IF(FLOWIN.LE.0.0) HSTR=STRM(5,L)
         CSTR=STRM(3,L)
         SBOT=STRM(4,L)
         H=HNEW(IC,IR,IL)
C***   set head to top active layer if dry cell
       IF(IBOUND(IC,IR,IL).EQ.0) H=HNEW(IC,IR,NIL)
        T=HSTR-SBOT
```

... skip lines...

```
C18----STREAMFLOW OUT EQUALS STREAMFLOW IN MINUS LEAKAGE.
  315 IF((IBOUND(IC,IR,IL).LE.0).AND.(NSTROP.EQ.1)) FLOBOT=0.
  320  FLOWOT=FLOWIN-FLOBOT
         IF((ISTSG.GT.1).AND.(NREACH.EQ.1)) STRM(9,LL)=ARTRIB(IFLG)
C
C19----STORE STREAM INFLOW, OUTFLOW AND LEAKAGE FOR EACH REACH.
         STRM(9,L)=FLOWOT
```

```
       STRM(10,L)=FLOWIN
       STRM(11,L)=FLOBOT
C
C20----IF LEAKAGE FROM STREAMS IS TO BE SAVED THEN ADD RATE TO BUFFER.
C------OPTION=3; LEAKAGE IS INTO HIGHEST CELL IN A VERTICAL COLUMN
C------THAT IS NOT NO FLOW. IF NO ACTIVE CELLS EXIST THEN ZERO STREAM
C------LEAKAGE
      IF ((IBD.EQ.1).AND.(FLOBOT.NE.0.0)) THEN
       IF (IBOUND(IC,IR,IL).GT.0)
        BUFF(IC,IR,IL)=BUFF(IC,IR,IL)+FLOBOT
       ELSE
        BUFF(IC,IR,NIL)=BUFF(IC,IR,NIL)+FLOBOT
       ENDIF
      ENDIF
C
C21----DETERMINE IF FLOW IS INTO OR OUT OF MODEL CELL.
```

... skip lines...

```
C29-----SAVE STREAMFLOWS OUT OF EACH REACH ON DISK.                  C
       DO 615 L=1,NSTREM
       IC=ISTRM(3,L)
       IR=ISTRM(2,L)
       IL=ISTRM(1,L)
       IF((IBOUND(IC,IR,IL).LE.0).AND.(NSTROP.EQ.1)) GO TO 615
       IF (IBOUND(IC,IR,IL).GT.0)
     & BUFF(IC,IR,IL)=BUFF(IC,IR,IL)+STRM(9,L)
C*** set layer to top active cell
      IF (IBOUND(IC,IR,IL).EQ.0.AND.NSTROP.EQ.3)
     & BUFF(IC,IR,NIL)=BUFF(IC,IR,NIL)+STRM(9,L)
  615 CONTINUE
```

APPENDIX 3: MULTI-AQUIFER WELL PACKAGE

```
SUBROUTINE MAW5AL(ISUM,LENX,MXMAW,NMAWS,IN,IOUT,
   1     NLAY,LCRMAW,LCRMAL,IMAWCB)
C
C-----VERSION 5.0 OCT2001 MAW5AL
C     ******************************************************************
C     ALLOCATE ARRAY STORAGE FOR MULTI-AQUIFER WELL PACKAGE
C     ******************************************************************
C
C1------IDENTIFY PACKAGE AND INITIALIZE NMAWS
      WRITE(IOUT,1)
    1 FORMAT(1H0,'MAW5 -- MULTI-AQUIFER WELL PACKAGE VERSION 5')
         NMAWS=0
C
C2------READ MAX NUMBER OF MAWS AND UNIT OR FLAG FOR
C2------CELL-BY-CELL FLOW TERMS.
      READ(IN,2) MXMAW,IMAWCB
    2 FORMAT(2I10)
      WRITE(IOUT,3) MXMAW
    3 FORMAT(1H ,'MAXIMUM OF',I5,' MULTI-AQUIFER WELL CATEGORIES')
      IF(IMAWCB.GT.0) WRITE(IOUT,9) IMAWCB
    9 FORMAT(1X,'CELL-BY-CELL FLOW  WILL BE SAVED ON UNIT',I3)
      IF(IMAWCB.LT.0) WRITE(IOUT,8)
    8 FORMAT(1X,'CELL-BY-CELL FLOWS WILL BE PRINTED WHEN ICBCFL NOT 0')
C
C3------ALLOCATE SPACE FOR ARRAYS RMAW AND RMAL.
      ISOLD=ISUM
      LCRMAW=ISUM
      ISUM=ISUM+5*MXMAW
      LCRMAL=ISUM
      ISUM=ISUM+4*NLAY*MXMAW
      ISP=ISUM-ISOLD
C
C4------PRINT NUMBER OF WORDS IN X ARRAY USED BY MAW PACKAGE.
      WRITE(IOUT,4) ISP
    4 FORMAT(1X,I6,' ELEMENTS IN X ARRAY ARE USED FOR MAWS')
      ISUM1=ISUM-1
      WRITE(IOUT,5) ISUM1,LENX
    5 FORMAT(1X,I6,' ELEMENTS OF X ARRAY USED OUT OF ',I13)
      IF(ISUM1.GT.LENX) WRITE(IOUT,6)
    6 FORMAT(1X,'   ***X ARRAY MUST BE DIMENSIONED LARGER***')
C
C5------RETURN
      RETURN
      END
C
```

```
      SUBROUTINE MAW5RP(RMAW,RMAL,NMAWS,MXMAW,IN,IOUT,
     1        NLAY)
C-----VERSION 5.0 OCT2001 MAW1RP
C     ****************************************************************
C     READ MULTI-AQUIFER WELL LOCATIONS AND STRESS RATES
C       modified by RMY to omit categories & read data from single line
C     ****************************************************************
C
C        SPECIFICATIONS:
C     --------------------------------------------------------------
      DIMENSION RMAW(5,MXMAW),RMAL(4,NLAY,MXMAW)
      INTEGER   LAYERS(10)
C     -------------------------------------------------------------
C
C1------READ ITMP(# OF MAW WELLS OR FLAG SAYING REUSE MAW DATA)
      READ (IN,1) ITMP
    1 FORMAT(I10)
      IF(ITMP.GE.0) GO TO 50
C
C2------IF ITMP LESS THAN ZERO REUSE DATA. PRINT MESSAGE AND RETURN.
      WRITE(IOUT,6)
    6 FORMAT(1H0,'REUSING MULTI-AQUIFER WELLS FROM LAST STRESS PERIOD')
      GO TO 260
C
C3------ITMP=>0.  SET NMAWS EQUAL TO ITMP.
   50 NMAWS=ITMP
      IF(NMAWS.LE.MXMAW) GO TO 100
C
C4------NMAWS > MXMAW.  PRINT MESSAGE. STOP.
      WRITE(IOUT,99) NMAWS,MXMAW
   99 FORMAT(1H0,'ITMP(',I4,') IS GREATER THAN MXMAW(',I4,')')
      STOP
C
C5------PRINT NUMBER OF MAW WELLS IN CURRENT STRESS PERIOD.
  100 WRITE (IOUT,2) NMAWS
    2 FORMAT(1H0,/
     +       1X,I5,' MULTI-AQUIFER WELLS')
C
C6------IF THERE ARE NO ACTIVE MAWS IN THIS STRESS PERIOD THEN RETURN
      IF(NMAWS.EQ.0) GO TO 260
C
C7------PRINT HEADING FOR MAW INPUT.
      WRITE(IOUT,3)
    3 FORMAT(1X,/
     +  1X,'      ROW    COL    M.A.W. RATE   RADIUS RATIO  WELL NO.',/
     +  1X,'-------------------------------------------------------')
      DO 250 II=1,NMAWS
C
C8------FOR EACH WELL READ AND PRINT ROW, COLUMN, RATE,
C8------# OF LAYERS SCREENED AND # IN CATEGORY.
            READ (IN,4) I,J,Q,RRATIO,NUM,(LAYERS(L),L=1,10)
    4 FORMAT(2I10,2F10.0,I5,10I3)
            WRITE (IOUT,7) I,J,Q,RRATIO,II
    7 FORMAT(2X,I8,I7,G16.5,F10.2,I8)
            RMAW(1,II)=I
      RMAW(2,II)=J
      RMAW(4,II)=RRATIO
C***    Q in Bennett et al (1982) is positive to for discharging well
C***    Q in this code is read as negative for discharging well
      RMAW(5,II)=-Q
      NWLAYS=0
      DO 230 L=1,10
      IF (LAYERS(L).EQ.0) GO TO 230
        NWLAYS=NWLAYS+1
        RMAL(1,NWLAYS,II)= L
```

```
  230 CONTINUE
      IF ((NWLAYS.ne.num).AND.(Q.ne.0)) THEN
        WRITE (IOUT,9) NUM,II
    9   FORMAT(5x,'NUMBER OF LAYERS NOT EQUAL',I5,' FOR WELL #',I5)
        STOP
      ENDIF
      RMAW(3,II)=NWLAYS
      WRITE(IOUT,8) (RMAL(1,JJ,II), JJ= 1,NWLAYS)
    8 FORMAT(1X,'LAYERS: ',10f5.0)
      DO 240 JJ=1,NWLAYS
C
C9------FOR EACH SCREENED LAYER READ LAYER # AND RADIUS RATIO.
      RMAL(2,JJ,II)=RRATIO
  240 CONTINUE
  250 CONTINUE
C
C10-----RETURN
  260 RETURN
      END
C
      SUBROUTINE MAW5FM(NMAWS,MXMAW,RHS,HCOF,IBOUND,RMAW,
     1        RMAL,NCOL,NROW,NLAY,CR,DELC,DELR,HNEW,IOUT)
C
C-----VERSION 5.0 OCT2001 MAW5FM
C
C     ******************************************************************
C     ADD MULTI-AQUIFER WELL FLOW TO RHS AND HCOF
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DOUBLE PRECISION HNEW
C
      DIMENSION RHS(NCOL,NROW,NLAY),HCOF(NCOL,NROW,NLAY),
     1    RMAW(5,MXMAW),
     2    RMAL(4,NLAY,MXMAW),CR(NCOL,NROW,NLAY),DELC(NROW),
     3    DELR(NCOL),HNEW(NCOL,NROW,NLAY),IBOUND(NCOL,NROW,NLAY)
C     ------------------------------------------------------------------
      PI=3.14159
C
C1------PROCESS EACH MAW CATEGORY
      DO 90 I1=1,NMAWS
C
C2------GET THE INFORMATION FOR THE CATEGORY
      NWLAYS=RMAW(3,I1)
      I=RMAW(1,I1)
      J=RMAW(2,I1)
      SUMF=0
      SUMFH=0
C
C3------PROCESS THE CELL IN EACH SCREENED LAYER
      DO 30 I2=1,NWLAYS
      K=RMAL(1,I2,I1)
C
C4------IF THE CELL IS NOT ACTIVE MOVE ON TO THE NEXT LAYER.
      IF(IBOUND(J,I,K).LE.0) GO TO 30
C
C5------CALCULATE THE TRANSMISSIVITY OF THE CELL.
      TRM=CR(J-1,I,K)*((DELR(J-1)+DELR(J))/2)/DELC(I)
      TRP=CR(J,I,K)*((DELR(J)+DELR(J+1))/2)/DELC(I)
      IF ((TRM.NE.0).AND.(TRP.NE.0)) GO TO 50
C
C6----IF EITHER TRANSMISSIVITY IS ZERO THEN CHECK TO SEE WHETHER
C     WELL EXTENDS TO LOWER LAYERS, IF NOT, STOP SIMULATION
      IF (I2.LT.NWLAYS) GO TO 30
```

```
      WRITE(IOUT,888) K,I,J
  888 FORMAT(1H ,’MAW FAILS. WELL IN LAYER’,I5,’ ROW’,I5,’ COLUMN’,
     1       I5,’ IS ADJACENT TO AN INACTIVE CELL’)
      WRITE(IOUT,889)
  889 FORMAT(1H ,’SIMULATION ENDING’)
      STOP
C
C7------CALCULATE F AND FH, STORE THEM IN ARRAY RMAL AND ADD THEM
C7------TO ACCUMULATORS SUMF AND SUMFH.
   50 TR=2*TRP*TRM/(TRP+TRM)
      RRATIO=RMAW(4,I1)
      F=TR/(ALOG(RRATIO))
      SUMF=SUMF+F
      RMAL(3,I2,I1)=F
      HTMP=HNEW(J,I,K)
      FH=F*HTMP
      SUMFH=SUMFH+FH
      RMAL(4,I2,I1)=FH
30    CONTINUE
C***    check for dry wells
      IF (sumf.eq.0) THEN
        WRITE(IOUT,890) I, J
  890   FORMAT(’ DRY WELL IN ROW ’,I5, ’ COLUMN ’,I5)
        GO TO 90
        ENDIF
C
C8------CALCULATE THE HEADS IN THE WELLS IN THIS CATEGORY
      Q=RMAW(5,I1)
      HWELL=(SUMFH/SUMF)-(Q/(2*PI*SUMF))
C
C9------FOR EACH CELL ADD TERMS FOR THIS CATEGORY TO HCOF AND RHS.
C***    categories omitted in this version
      DO 60 I2=1,NWLAYS
      K=RMAL(1,I2,I1)
      IF(IBOUND(J,I,K).LE.0) GO TO 60
      F=RMAL(3,I2,I1)
      NINCAT=1
      HCOF(J,I,K)=HCOF(J,I,K)-2*PI*F*NINCAT
      RHS(J,I,K)=RHS(J,I,K)-2*PI*F*HWELL*NINCAT
60    CONTINUE
90    CONTINUE
C
C10-----RETURN
      RETURN
      END
      SUBROUTINE MAW5BD(NMAWS,MXMAW,IBOUND,RMAW,
     1       RMAL,NCOL,NROW,NLAY,HNEW,KSTP,KPER,IMAWCB,
     2       ICBCFL,BUFF,IOUT,MSUM,DELT,VBNM,VBVL)
C-----VERSION 5.0 OCT2001 MAW5BD
C
C     ******************************************************************
C     CALCULATE CELL-BY-CELL FLOWS AND BUDGET TERMS FOR
C     MULTI-AQUIFER WELLS
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DOUBLE PRECISION HNEW
C
      DIMENSION HNEW(NCOL,NROW,NLAY),IBOUND(NCOL,NROW,NLAY),
     1  RMAW(5,MXMAW),
     2  RMAL(4,NLAY,MXMAW),
     3  BUFF(NCOL,NROW,NLAY),VBVL(4,20),VBNM(4,20)
      DIMENSION TEXT(4)
      CHARACTER*4 TEXT,VBNM
```

```
      DATA TEXT(1),TEXT(2),TEXT(3),TEXT(4) /'MULT','I-AQ','IFR ','WELL'/
C     ------------------------------------------------------------------
C
C1------CLEAR RATIN AND RATOUT ACCUMULATORS.
      IBD=0
      RATIN=0.
      RATOUT=0.
C
C2------IF THERE ARE NO MAWS DO NOT ACCUMULATE FLOW
      IF(NMAWS.EQ.0)GO TO 200
C
C3------TEST TO SEE IF CELL-BY-CELL FLOW TERMS WILL BE RECORDED.
      IF(ICBCFL.EQ.0  .OR. IMAWCB.LE.0 ) GO TO 10
C
C4------IF CELL-BY-CELL FLOWS WILL BE SAVED THEN CLEAR THE BUFFER.
      IBD=1
      DO 5 IL=1,NLAY
      DO 5 IR=1,NROW
      DO 5 IC=1,NCOL
      BUFF(IC,IR,IL)=0.
    5 CONTINUE
C
C5------PROCESS MAW CATEGORIES ONE AT A TIME.
   10 PI=3.14159
      DO 150 I1=1, NMAWS
      NWLAYS=RMAW(3,I1)
      I=RMAW(1,I1)
      J=RMAW(2,I1)
      SUMF=0
      SUMFH=0
C
C5A-----FOR EACH CELL OPEN TO THE CATEGORY CALCULATE F AND FH
      DO 30 I2=1,NWLAYS
      K=RMAL(1,I2,I1)
      IF(IBOUND(J,I,K).LE.0) GO TO 30
      F=RMAL(3,I2,I1)
      SUMF=SUMF+F
      HTMP=HNEW(J,I,K)
      FH=F*HTMP
      SUMFH=SUMFH+FH
      RMAL(4,I2,I1)=FH
30    CONTINUE
C***    skip over if dry well
      IF (sumf.eq.0) GO TO 150
C
C5B-----CALCULATE THE HEAD IN THE WELLS IN THIS CATEGORY
      Q=RMAW(5,I1)
      HWELL=(SUMFH/SUMF)-(Q/(2*PI*SUMF))
C
C5C-----FOR EACH LAYER IN WHICH THE MAW IS SCREENED PROCESS
C5C-----THE CELL WHICH CONTAINS THE MAW.
      DO 100 I2=1,NWLAYS
C
C5C1----CALCULATE RATE OF FLOW FROM THE MAWS INTO THE CELL.
      K=RMAL(1,I2,I1)
      IF(IBOUND(J,I,K).LE.0) GO TO 100
      F=RMAL(3,I2,I1)
      HTMP=HNEW(J,I,K)
      NINCAT=1
      RATE=2*PI*F*(HWELL-HTMP)*NINCAT
C
C5C2----IF BUDGET TERMS ARE TO BE SAVED THEN ADD RATE TO BUFFER.
            IF(IBD.EQ.1) BUFF(J,I,K)=BUFF(J,I,K)+RATE
C
C5C3----PRINT THE INDIVIDUAL RATES IF REQUESTED(IMAWCB<0).
```

```
      IF(IMAWCB.LT.0.AND.ICBCFL.NE.0) WRITE(IOUT,900) (TEXT(N),N=1,4),
     1    KPER,KSTP,I1,K,I,J,RATE,HWELL
  900 FORMAT(1H0,4A4,'    PERIOD',I3,'    STEP',I3,'     MAW',I4,
     1    '    LAYER',I3,'    ROW ',I4,'    COL',I4,'    RATE',G15.7,
     2    '    HWELL',G15.7)
      IF(RATE) 90,100,80
C
C5C4---- RATE IS POSITIVE(RECHARGE). ADD IT TO RATIN.
   80 RATIN=RATIN+RATE
      GO TO 100
C
C5C5----RATE IS NEGATIVE(DISCHARGE). ADD IT TO RATOUT.
   90 RATOUT=RATOUT-RATE
  100 CONTINUE
  150 CONTINUE
C
C6------IF CELL-BY-CELL TERMS WILL BE SAVED THEN CALL UBUDSV TO
C6-----RECORD THEM ON DISK
      IF(IBD.EQ.1) CALL UBUDSV(KSTP,KPER,TEXT,IMAWCB,BUFF,NCOL,NROW,
     1                       NLAY,IOUT)
C
C7------MOVE RATES INTO VBVL FOR PRINTING BY MODULE BAS1OT.
  200 VBVL(3,MSUM)=RATIN
      VBVL(4,MSUM)=RATOUT
C
C8------MOVE RATES TIMES TIME STEP LENGTH INTO VBVL ACCUMULATORS.
      VBVL(1,MSUM)=VBVL(1,MSUM)+RATIN*DELT
      VBVL(2,MSUM)=VBVL(2,MSUM)+RATOUT*DELT
C
C9------MOVE BUDGET TERM LABELS INTO VBNM FOR PRINTING.
      VBNM(1,MSUM)=TEXT(1)
      VBNM(2,MSUM)=TEXT(2)
      VBNM(3,MSUM)=TEXT(3)
      VBNM(4,MSUM)=TEXT(4)
C
C10-----INCREMENT BUDGET TERM COUNTER(MSUM).
      MSUM=MSUM+1
C
C11-----RETURN
      RETURN
      END
```

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BOOK RATE

C.E. Heywood and R.M. Yager—SIMULATED GROUND-WATER FLOW IN THE HUECO BOLSON, AN ALLUVIAL-BASIN AQUIFER SYSTEM NEAR EL PASO, TEXAS—U.S. Geological Survey Water-Resources Investigations Report 02-4108