# PRELIMINARY STUDY OF THE AQUIFERS OF THE LOWER MESILLA VALLEY IN TEXAS AND NEW MEXICO BY MODEL SIMULATION

By J. S. Gates, D. E. White, and E. R. Leggat

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ILLUSTRATIONS

## METRIC CONVERSIONS

Factors for converting inch-pound units to metric equivalents are given in the following table:

| From | Multiply by | To obtain |
|---|---|---|
| acre | 0.4047 | hectometer |
| acre-foot (acre-ft) | 1,233.6 | cubic meter |
| acre-foot per acre | 0.3048 | meter |
| acre-foot per year (acre-ft/yr) | 1,233.6 | cubic meter per year |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second |
| foot (ft) | 0.3048 | meter |
| foot per day (ft/d) | 0.3048 | meter per day |
| foot per acre per year | 0.7532 | meter per hectometer per year |
| foot squared per day ($ft^2/d$) | 0.09290 | meter squared per day |
| inch (in.) | 25.40 | millimeter |
| mile (mi) | 1.609 | kilometer |

# PRELIMINARY STUDY OF THE AQUIFERS OF THE LOWER MESILLA VALLEY IN TEXAS AND NEW MEXICO BY MODEL SIMULATION

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ABSTRACT

The aquifers in the lower Mesilla Valley of Texas and New Mexico provide water for irrigation, industrial use, and municipal supply. At present (1984), the shallow aquifer is used principally for irrigation. The medium-depth aquifer (the top of which is about 160 to 260 feet below land surface) and deep aquifer (about 460 to 680 feet below land surface) are used almost exclusively by the city of El Paso to provide about 28 percent of the city's ground-water withdrawal of about 82,000 acre-feet in 1980; however, a small percentage of the pumpage is from the shallow aquifer. The potential use of the medium-depth and deep aquifers for irrigation, together with a planned increase in pumping by the city, is causing concern on the part of El Paso water planners over the impact of this development on the limited supply from the two aquifers.

A three-dimensional digital model of the aquifers was developed to evaluate the responses of water levels to various plans of development, with particular emphasis on the medium-depth and deep aquifers in and near the Canutillo well field. Simulations also were made to show the effect of eliminating seepage from the Rio Grande to the aquifer system.

The model simulations indicate that if pumpage by the city of El Paso during 1976-80 increases to 10,000 acre-feet per year from the medium-depth aquifer and to 20,000 acre-feet per year from the deep aquifer, and elsewhere in the study area pumping was held constant at the 1975 rate, then additional lowering of water levels in representative observation wells would be as much as 24 feet in the medium-depth aquifer and as much as 52 feet in the deep aquifer. The water levels would decline sharply during the first few months, after which the levels would become nearly stable because the leakage between the aquifers probably is enough to balance the increased pumpage. The model also indicated that lining of the channel of the Rio Grande would result in an additional lowering of water levels in representative observation wells by 10 feet in the medium-depth aquifer and 8 feet in the deep aquifer.

The accuracy of water levels simulated by a model is dependent on the accuracy and distribution of input data and how well model boundary conditions approximate actual boundary conditions. Because of a lack of hydrologic data (especially water-level information) everywhere except the Canutillo well-field area, because the simulated cone of depression reached two boundaries, and because the model contained an error and several deficiencies as explained in the "Discussion" section, the simulated results need to be interpreted carefully. The authors believe that the simulated results could be used best as a

preliminary and conceptual evaluation of the pumping effects at the Canutillo well field, not as a quantitative interpretation. Although the patterns of simulated hydrographs of water-level change in observation wells in the Canutillo field generally may be correct, the amount of change simulated probably is not correct.

Because the salinity of water in all three aquifers south of Canutillo is greater than elsewhere in the study area, there is potential for movement of this water northward toward the Canutillo well field if the cone of depression reaches that part of the aquifer system. This potential should be evaluated in future geohydrologic studies of the lower Mesilla Valley.

# INTRODUCTION

Prior to 1956, the ground-water needs of the city of El Paso were supplied mainly from wells in the Hueco bolson and from about 12 shallow wells in the Canutillo well field in the lower Mesilla Valley (figs. 1 and 2). In 1956, the city began to develop the deeper aquifers in the Canutillo well field, and by the end of 1975, the city had drilled six wells in the deep aquifer, the top of which is about 460 to 680 ft below land surface, nine wells in the medium-depth aquifer, the top of which is about 160 to 260 ft below land surface, and four additional wells in the shallow aquifer. All the wells are in that part of the valley bounded on the west by the New Mexico-Texas State line, on the north and east by the Rio Grande, and on the south by an east-west line just north of Canutillo, Texas (fig. 2).

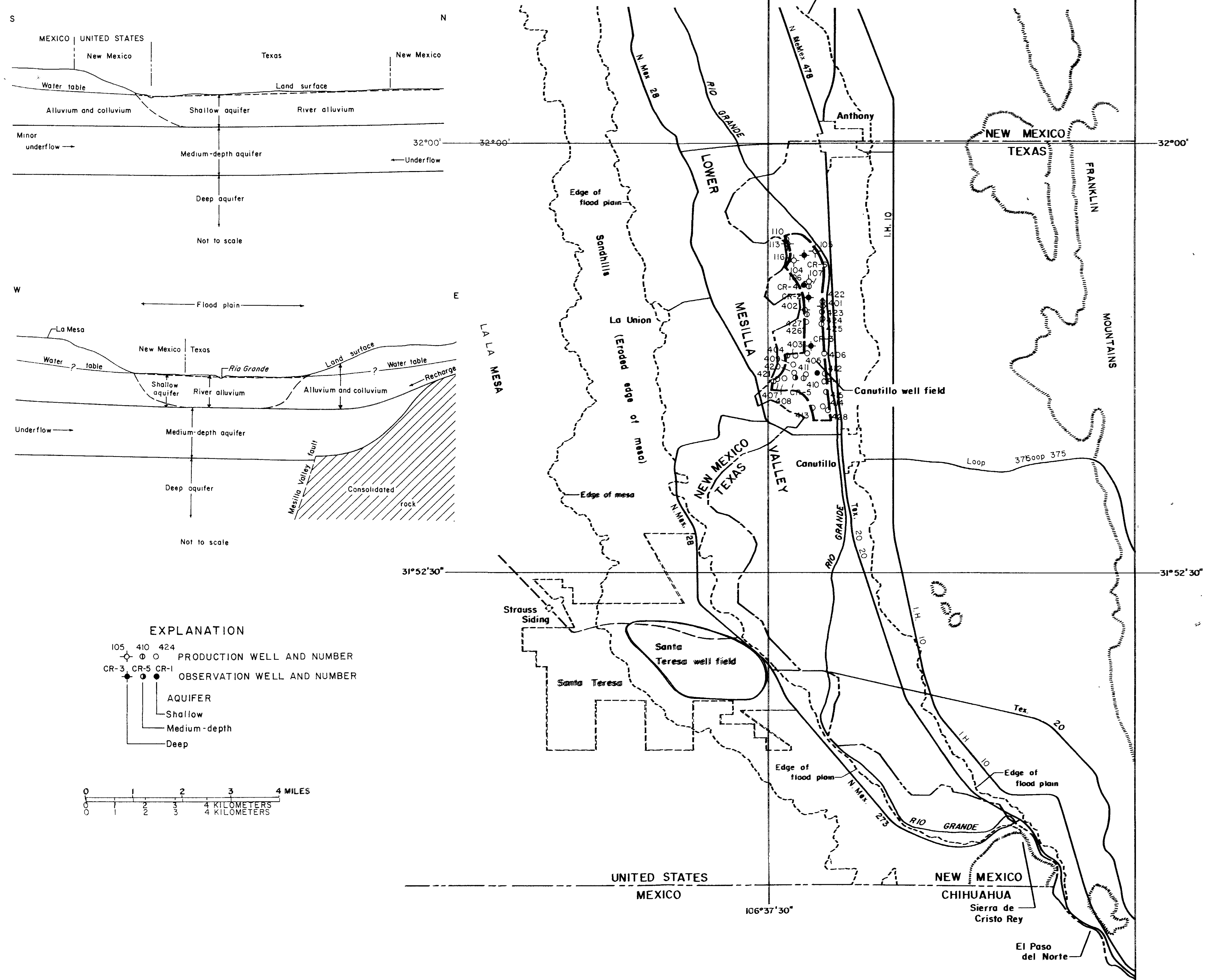
The city pumps water from the shallow wells into the Rio Grande during the irrigation season when water is released from the river's upstream storage. This pumpage, less the transportation loss and plus the city's surface-water allotment, is diverted to a treatment plant near downtown El Paso. Water from the medium-depth and deep aquifers is piped directly to the distribution system. At present (1984), almost all the ground water used for agriculture is obtained from the shallow aquifer, whereas the city obtains water from the deep and medium-depth aquifers, as well as from the shallow aquifer. The city obtained about 28 percent of its total water supply (about 82,000 acre-ft) in 1980 from the Canutillo field.

Recently, interest has increased in the potential of the medium-depth and deep aquifers as a source of water for irrigation not only in the Mesilla Valley but also in the El Paso Valley to the southeast. As a consequence, the city has become increasingly concerned that such development, coupled with their own planned increases in pumping, would have a serious impact on the limited water supplies available from the medium-depth and deep aquifers. This concern is compounded by the New Mexico State law that prohibits the transportation of ground water across the State line, thereby effectively closing the areas west and north of the Canutillo field to development by the city.

## Purpose and Scope

The purpose of this study, conducted in cooperation with the Texas Department of Water Resources and El Paso Water Utilities, was to develop a digital model of the lower Mesilla Valley that would reasonably simulate known responses of water levels to pumping stresses and, consequently, would predict (1) the effects on water levels of alternative plans of development, and (2) the effects of a hypothetical lining of the channel of the Rio Grande with concrete, as has been done for the Rio Grande at El Paso. The principal concern of the study was the effects of pumping stresses on water levels in the medium-depth and deep aquifers, with primary emphasis on the area of the Canutillo well field (fig. 2). Unfortunately, there is not enough information, especially water-level information, on the aquifer system except in the Canutillo well field to perform a detailed analysis.

This report briefly presents the results of (1) a steady-state analysis of the hydrologic conditions prior to 1952 (predevelopment), (2) transient-state analyses for 1952-67 and 1968-75, and (3) evaluation of water-level changes for




Base from U.S. Geological Survey
topographic quadrangles

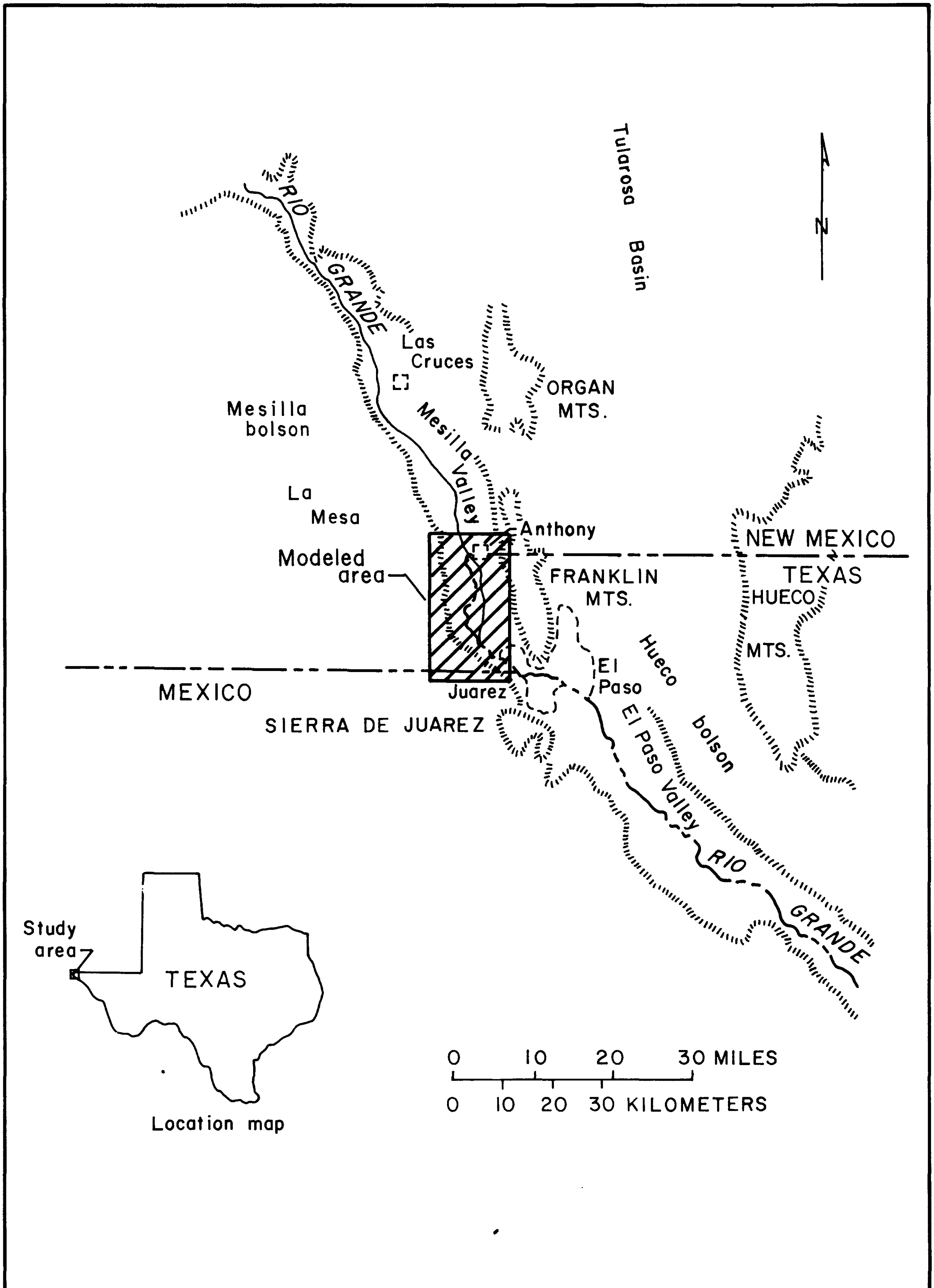



Figure 1.-Location of the lower Mesilla Valley and modeled area

1976-80, when pumping would be increased. In addition, the model was used to estimate the effects of an assumed lining of the Rio Grande during 1976-80. Because of a lack of data everywhere in the study area except the Canutillo well field, many estimates were made to construct the model. Thus, the model calibration only uses water-level data in the Canutillo well field, which is a small part of the lower Mesilla Valley; therefore, the information presented in this report needs to be considered qualitative.

### Previous Investigations

The geology and hydrology of the lower Mesilla Valley have been described in several reports, the most pertinent to the present study being those by Conover (1954), Leggat and others (1963), and Gates and others (1978). Unpublished data in the files of El Paso Water Utilities were used extensively in the study.

## GEOHYDROLOGY

The lower Mesilla Valley is underlain by unconsolidated deposits of gravel, sand, silt, and clay to depths of at least 1,200 ft. A well in the valley was drilled into igneous rock at 1,271 ft; and a well southwest of the valley flood plain penetrated what probably was semiconsolidated deposits at 1,810 ft. The deposits in the lower Mesilla Valley have been divided into three aquifers on the basis of (1) differences in lithology, (2) characteristic responses on electrical logs of wells in the Canutillo well field, (3) chemical quality of the water, and (4) different water levels under the stress of pumping. The diagrammatic sections in figure 2 show the relation between the aquifers and geographic features of the lower Mesilla Valley.

The shallow aquifer (designated as layer 3 in the simulation model), which consists mainly of gravel and coarse sand and averages about 200 ft in thickness, is near the land surface in the Canutillo well field. This unit occurs principally within the flood plain of the valley, although it grades into less permeable sediments east and west of the boundaries of the flood plain. The medium-depth aquifer (designated as layer 2 in the simulation model), which consists of finer sand and smaller amounts of gravel than the shallow aquifer, lies at a depth of about 160-260 ft and has an average thickness of about 400 ft. The deep aquifer (designated as layer 1 in the simulation model), which consists of uniformly fine sand, occurs at a depth of about 460-680 ft and has an average thickness of about 600 ft.

Both the medium-depth and deep aquifers probably extend westward beyond the flood plain, although few deep wells have been drilled outside the Canutillo well field. Along the eastern edge of the valley, the deep aquifer probably terminates sharply against a fault (see section, fig. 2) that was inferred by Gates and others (1978, p. 102) on the basis of data from electrical resistivity surveys made by Zohdy and others (1976).

Ground water occurs under unconfined conditions in the shallow aquifer and in the lateral equivalents to the shallow aquifer outside the flood plain. Water in the medium-depth and deep aquifers probably is under confined conditions within the flood plain. West of the flood plain, the sediments may form one hydrogeologic unit under unconfined conditions or the lower part of the unit (about the lateral equivalents of the medium-depth and deep aquifers) may be under confined conditions. Under natural conditions, water levels are progressively higher with depth under the flood plain because ground water moves from the mesa toward the center of the Mesilla Valley and discharges to the Rio Grande and the flood plain near the river.

No areally extensive confining beds are known between the shallow and medium-depth aquifers or between the medium-depth and deep aquifers in the lower Mesilla Valley. However, discontinuous clay lenses or layers that are relatively impermeable exist within the flood plain and retard vertical flow.

Conditions in the lower Mesilla Valley area are assumed to be similar to those in the Hueco bolson, the next basin downstream along the Rio Grande. In the Hueco bolson, aquifer tests within the flood plain indicate water under artesian conditions. Water-level fluctuations (Knowles and Kennedy, 1956, p. 37) and long-term aquifer tests outside the flood plain in the Hueco bolson indicate that water is under water-table conditions, although the sediments are similar in areas outside and within the flood plain. However, the exact location of the transition zone between the semiartesian and water-table conditions is not known. Meyer (1976) constructed a digital model of this area for which coefficients of storage in the artesian range were assigned arbitrarily to the part of the aquifer under the flood plain, and coefficients of storage (specific yields) in the water-table range were assigned to the remainder of the modeled area. Meyer's model was able to reproduce historical water-level changes in the Hueco bolson.

In the lower Mesilla Valley, aquifer tests of the medium-depth and deep aquifers under and near the flood plain of the Rio Grande indicate that water is under artesian conditions. No aquifer tests were made on La Mesa. Storage coefficients in the medium-depth and deep aquifers probably vary from artesian range under the flood plain to water-table range under parts of La Mesa (where the medium-depth and deep aquifers, along with the lateral equivalents of the shallow aquifer, may form a single hydrologic unit). For the model described in this report, the boundary between water-table and artesian conditions arbitrarily was assumed to correspond to the edge of the flood plain, similar to the assumptions made for the Hueco bolson model by Meyer (1976).

Recharge to the shallow aquifer primarily is seepage from canals and the Rio Grande and infiltration of irrigation water. Lateral ground-water flow from uplands to the east and west and from the upstream part of the Mesilla Valley probably recharges all three aquifers. Because the potential annual evaporation (96 in.) greatly exceeds the average annual rainfall (8 in.), recharge from precipitation on the flood plain probably is insignificant and negligible. Discharge of ground water primarily is by pumping, evapotranspiration from phreatophyte areas in the flood plain, and seepage to the Rio Grande and irrigation drains. Underflow out of the valley probably is negligible.

The quality of water in the aquifers of the lower Mesilla Valley varies considerably, both areally and with depth. In general, the water in the shallow aquifer is more saline than the deeper ground water. Water from the medium-depth and deep aquifers in the Canutillo-Anthony area is of good quality, the best of which, from the deep aquifer, commonly contains less than 300 mg/L (milligrams per liter) dissolved solids.

Leggat and others (1963, p. AA36) observed that the base of the freshwater (water containing less than 1,000 mg/L dissolved solids) in the three aquifers is at a depth of at least 1,200 ft in the Canutillo well field, but that it is progressively shallower toward the south and east. South of Canutillo, ground-water quality decreases and water contains from 1,000 to more than 20,000 mg/L of dissolved solids. If the cone of depression in the potentiometric surface extends farther to the south of Canutillo due to increases in pumpage, this more-saline water could move towards the well field.

Prior to 1957, water movement in all three aquifers probably was toward the Rio Grande, which was the primary discharge zone for much of the Mesilla bolson's ground-water system. Ground water also moved south from the northern part of the Mesilla Valley and from the uplands east and west of the lower Mesilla Valley and discharged to the river. Water in the medium-depth and deep aquifers moved upward to the shallow aquifer under the river flood plain.

Also prior to 1957, most of the ground water used in the lower Mesilla Valley was obtained from the shallow aquifer and used for irrigation, although some ground water was pumped for municipal supply and industrial use. Pumping from the medium-depth and deep aquifers in the Canutillo well field began in the late 1950's, increased to the early 1960's, and subsequently remained fairly uniform (fig. 3). Pumpage from the Canutillo well field in 1975 for municipal and industrial use was 12,726 acre-ft from the deep aquifer, 1,438 acre-ft from the medium-depth aquifer, and 4,968 acre-ft from the shallow aquifer. In 1975, pumpage from the three aquifers in the entire lower Mesilla Valley for municipal and industrial uses totaled 27,096 acre-ft, of which 13,192 acre-ft was from the deep aquifer, 5,437 acre-ft from the medium-depth aquifer, and 8,467 acre-ft from the shallow aquifer.

Historically, water levels in the shallow aquifer in the lower Mesilla Valley have varied both seasonally and from year to year and have been most affected by the availability of surface water. Records since the early 1950's show that seasonal and annual water-table declines are caused by periods of insufficient surface-water supplies and increases in pumpage; however, the magnitude of the decline seldom exceeds 5 ft. During wet periods, the water table recovered completely, resulting in discharge of ground water to the Rio Grande and to irrigation drains.

In the medium-depth and deep aquifers, however, the relatively uniform rate of withdrawals has created a cone of water-level decline that varies in depth according to the distance from the pumping wells. Measurements made in two observation wells (CR-2 and CR-3, fig. 3) within the Canutillo well field show water-level declines of as much as 68 ft during 1957-75. Well records also show that when the well field was shut down, water levels rose sharply within a short interval, and recovery was a significant part of the total water-level decline.

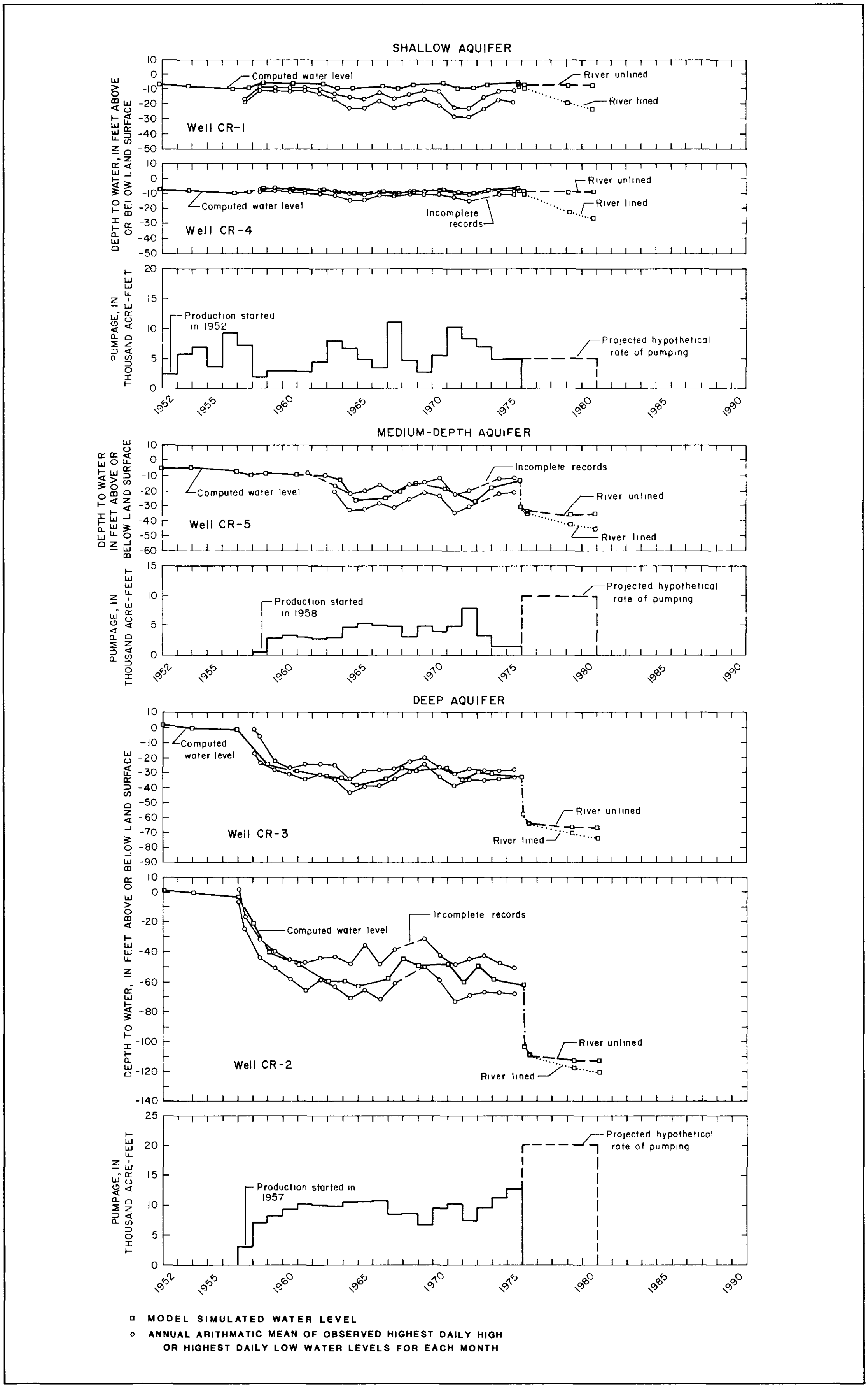



**FIGURE 3.-Hydrographs showing computed and observed water levels for selected observation wells, and annual pumpage, 1952-80 in the shallow, medium-depth, and deep aquifers in the Canutillo well field**

# THE DIGITAL MODEL

Water in the aquifers of the lower Mesilla Valley has a significant component of vertical flow. Prior to development, the flow was upward, but as a result of pumping from the medium-depth and deep aquifers (beginning in 1957), water levels declined sharply in those aquifers, and the flow was reversed in the vicinity of the Canutillo well field. Within a few years after pumping started (essentially by 1962), water levels in both the medium-depth and deep aquifers became relatively stable. This indicates the possibility that downward leakage balanced any excess of pumpage over other inflow to the aquifer. A three-dimensional finite-difference ground-water flow model was used to simulate the hydrologic condition of the aquifer system. Theoretical discussion of the model is given by Trescott (1975) and Trescott and Larson (1976).

A 23 by 46 rectangular grid system was used, which ranged in size from 0.25 x 0.25 mi in the Canutillo well field to 0.75 x 1 mi at the corners of the model (fig. 4).

The following parameters were entered in the model at each node for each aquifer:

1. Initial hydraulic head, in feet.
2. Transmissivity, in feet squared per day; and hydraulic conductivity, in feet per day (layer 3, the shallow aquifer).
3. Specific yield or storage coefficient.

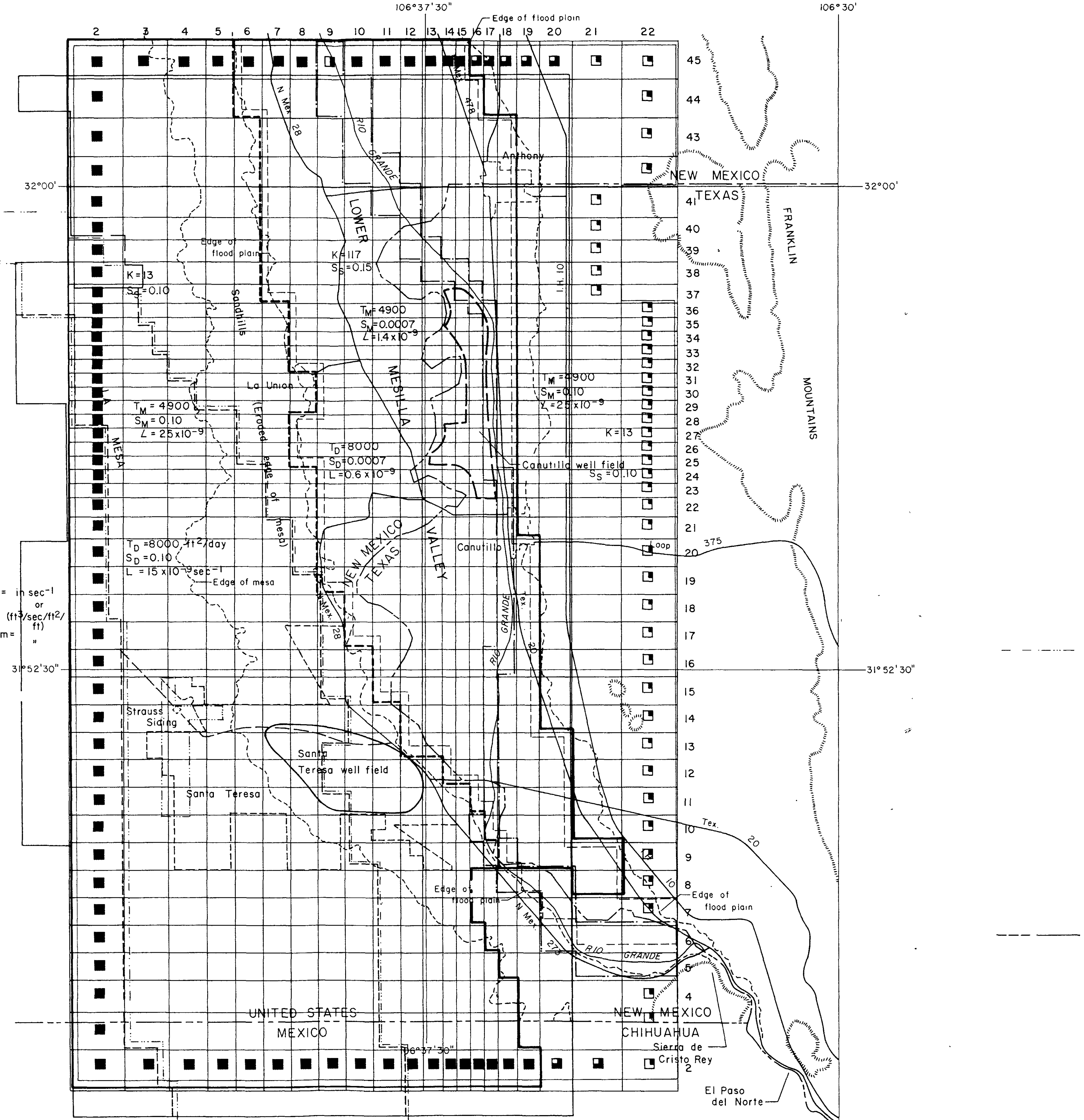
The following parameters were entered at appropriate nodes:

1. Vertical permeability between the shallow and medium-depth aquifers, and between the medium-depth and deep aquifers. This parameter is actually entered in the model as leakance ($K'/b'$), where $K'$ is vertical permeability and $b'$ is the distance between the centers of adjacent aquifers.
2. Discharge by wells, in cubic feet per second.
3. Recharge along the model boundaries, in cubic feet per second.

Recharge wells were assigned around the boundaries to simulate underflow into and recharge to the study area. The eastern boundary and southeastern corner of the model coincide with the occurrence of relatively impermeable consolidated rock; therefore, the underflow probably is derived only from local recharge which enters the shallow aquifer. Recharge wells along these parts of the model boundary were assigned to that aquifer only. In parts of the southeastern and northeastern boundaries, the deep aquifer does not exist, and underflow enters only the medium-depth and shallow aquifers. Therefore, at the few nodes along these parts of the boundary, recharge wells were assigned to both shallow and medium-depth aquifers. For the rest of the boundary, recharge wells were assigned to all three aquifers.

## Initial Hydraulic Head

Initial hydraulic heads for each node in the three aquifers were estimated from measurements made mostly during 1952-58 by Leggat and others (1962) in the floodplain area and from available measurements made at anytime outside the flood plain.




EXPLANATION

MODELED BOUNDARY OF DEEP AQUIFER (LAYER 1)--Dashed line indicates subareas of different values of transmissivity or storage

MODELED BOUNDARY OF MEDIUM-DEPTH AQUIFER (LAYER 2).--Dashed line indicates subareas of different values of transmissivity or storage

MODELED BOUNDARY OF SHALLOW AQUIFER (LAYER 3)--Dashed line indicates subareas of different values of transmissivity or storage

■ NODE WHERE RECHARGE IS SIMULATED TO ALL THREE LAYERS

NODE WHERE RECHARGE IS SIMULATED TO DEEP AND MEDIUM-DEPTH AQUIFERS (LAYERS 1 AND 2)

NODE WHERE RECHARGE IS SIMULATED TO MEDIUM-DEPTH AND SHALLOW AQUIFERS (LAYERS 2 AND 3)

NODE WHERE RECHARGE IS SIMULATED TO SHALLOW AQUIFER ONLY (LAYER 3)

CONSTANT-HEAD NODES (RIO GRANDE)

OUTLINE OF IRRIGATED LANDS AS ASSUMED FOR MODEL

| AQUIFER | TRANSMISSIVITY OR HYDRAULIC CONDUCTANCE | STORAGE COEFFICIENT OR SPECIFIC YIELD | K'/b' LEAKANCE |
|---|---|---|---|
| DEEP | $T_D$ = f$^2$/d | $S_D$ | L (Between deep and medium-depth aquifer) = in sec$^{-1}$ or (ft$^3$/sec/ft$^2$/ft) |
| MEDIUM-DEPTH | $T_M$ = f$^2$/d | $S_M$ | $\mathit{L}$ (Between medium and shallow) = " |
| SHALLOW | K = f/d | $S_S$ | |

0 1 2 3 4 MILES
0 1 2 3 4 KILOMETERS

Base from U.S. Geological Survey topographic quadrangles

## Transmissivity

Because of the scarcity of data, the transmissivity values determined for the three aquifers in the Canutillo well field were assumed to be applicable throughout the study area (fig. 4). On the basis of aquifer tests made by Leggat and others (1963), a hydraulic-conductivity value of 90 ft/d initially was assigned to that part of the shallow aquifer within the floodplain area. This parameter value was increased during model calibration to about 117 ft/d (an average transmissivity of about 23,400 $ft^2/d$).

Outside the floodplain area, the equivalent of the shallow aquifer is assumed to have an average hydraulic conductivity of 13 ft/d (transmissivity on the order of 3,000 $ft^2/d$, depending on the thickness of saturated aquifer). The same hydraulic conductivity of 13 ft/d also was assigned to the medium-depth and deep aquifers. The average transmissivity of the medium-depth and deep aquifers was calculated from the hydraulic conductivity of 13 ft/d times the average thickness of the aquifers. These values were 4,900 and 8,000 $ft^2/d$ for the medium-depth and deep aquifers, respectively, and were close to the values determined by Leggat and others (1963) and from tests by the city of El Paso (T. E. Cliett, oral commun., 1976).

## Specific Yield and Storage Coefficient

The specific yield in all the aquifers where water is assumed to be under water-table conditions was assumed to be 0.10 (this probably is in error, see "Discussion" section), except in the shallow aquifer under the flood plain (river alluvium) where it was assumed to be 0.15. The coefficient of storage in the medium-depth and deep aquifers under the flood plain, where water is assumed to be under semiartesian conditions, was assumed to be 0.0007 as estimated from aquifer tests made by Leggat and others (1963).

## Vertical Permeability

Vertical permeabilities (leakances) initially were estimated from aquifer tests made by Leggat and others (1963). These initial values were later decreased during model simulation by 50 percent between the deep and medium-depth aquifers for area in the flood plain and 70 to 85 percent between the medium-depth and shallow aquifers (70 percent for the area representing the flood plain, 85 percent for the area simulating the river). The latter decrease represents the permeability of the river bed. The final values of the leakances are shown in figure 4.

## Discharge by Wells

Pumpage from each well in the medium-depth and deep aquifers was compiled from records of El Paso Water Utilities and other users and entered into the model at each node occupied by wells. The grid network used in the model was positioned so as to reduce to a minimum the number of nodes in the Canutillo well field containing more than one well per aquifer.

Pumpage from the shallow aquifer was entered where data were available; other pumpage data, including irrigation pumpage from the shallow aquifer and pumpage from the medium-depth aquifer used for the Santa Teresa residential and golf-course development in the southwestern part of the valley (fig. 2), could only be estimated. Nevertheless, the lack of accuracy of these data was not considered to be crucial, because most of the estimated pumpage was either from the shallow aquifer or from deeper wells distant from the Canutillo well field; it is not known whether these inaccuracies in data affect the evaluation of effects on the well field. Layer 3, representing the shallow aquifer for the purpose of this study, was modeled mainly as a sink or source that transmits water to or from the medium-depth aquifer, rather than as an aquifer in which stress and its effect on water levels are studied in detail.

## Recharge

Underflow across the western and northern boundaries was calculated by Darcy's law and the estimated hydraulic gradient and transmissivity and then was assigned to each layer in proportion to its transmissivity. On the east side, recharge was calculated in the same manner, but was assigned only to the shallow aquifer because the medium-depth and deep aquifers probably pinch out to the east (see cross sections shown in fig. 2). At the south end, a small amount of recharge, calculated in the same manner, was assumed to enter the valley from the southwest and was assigned to all layers (where the aquifers are present) in proportion to their transmissivity.

Recharge from irrigation using surface water and ground water was estimated on the basis of surface-water availability. The required amount of irrigation water was assumed to be 3 acre-ft per acre. The infiltration rate was assumed to be 40 percent of the water applied for irrigation. When the amount of surface water available for irrigation was less than 3 acre-ft per acre, the difference was assumed to be made up by ground water pumped from the shallow aquifer. Also, 60 percent of the ground water was assumed to be consumptively used (because the assumed infiltration rate of irrigation water was 40 percent).

Because infiltration of irrigation water into the shallow aquifer was simulated, computer codes of Trescott (1975) and Trescott and Larson (1976) were modified during this study. The following statements were substituted for statement DAT 1810 in subroutine DATAIN of Trescott (1975):

```
260     READ (5,330) SW
        GW = (3.0-SW)
        IF (GW.LT.0.DO) GW = 0.0
        SEEP = (SW * SPFACT - GW * (1.0 - SPFACT))
        IF(SEEP.EQ.0.DO) SEEP = 0.1      (maintains non-zero values of SEEP and
                                          QRE at irrigated nodes)
        SEEP = SEEP/(365.25*86400.)
        DO 265 I = 1,IO
        DO 265 J = 1,JO
265     IF (QRE (I,J).NE.0.DO)           (non-zero values of QRE indicate nodes
           QRE(I,J) = SEEP                where infiltration from irrigation
                                          occurs)
        WRITE (6,490) SW, SEEP
        RETURN
```

Where: SW = annual allocation of water from the Rio Grande, in feet per acre per year;

GW = annual ground-water withdrawals to make up an estimated total irrigation supply of 3 ft per acre;

SEEP = seepage from irrigated land to the water table, in feet per year; and

SPFACT = the percentage of applied irrigation water assumed to percolate to the water table.

The Rio Grande was simulated with constant-level nodes in the shallow aquifer, which results in the river in effect cutting into the aquifer by half its thickness, or about 100 ft. At the time of this study, the computer code of Trescott (1975) and Trescott and Larson (1976) did not have features which allowed simulation of a river in the uppermost model layer. Because the scope of this study was limited, their code was not modified to include such features. Although the shallow aquifer was not modeled in detail in this study, the method of simulating the river probably would create errors, but are not believed to be critical to the results.

The modeled areas of the shallow, medium-depth, and deep aquifers, the values of aquifer parameters, the outline of the irrigated area, and the locations of constant-head nodes simulating the Rio Grande are shown in figure 4. In addition, values of transmissivity in the shallow aquifer and values for the leakance between the shallow and medium-depth aquifers along the boundary between the flood-plain area and the area outside of the flood plain were gradually decreased outside the boundary to avoid abrupt changes in transmissivity and leakance. These gradations were made by adding two intermediate values at two rows of nodes adjacent to the flood plain, but were not shown in figure 4 to avoid cluttering the map.

## Calibration of the Model

The model was calibrated (1) by matching computed water levels with predevelopment (steady-state) water levels as determined in part from historical records, principally measurements of water levels in wells by Leggat and others (1962); and (2) by simulating pumping during 1952-67 and comparing the computed water levels with the observed water levels.

Steady-state conditions were simulated when the computed water levels compared favorably with the predevelopment water levels, principally for the medium-depth and deep aquifers (water-level maps are not shown in report). Adjustments in the following parameters were made during 10 steady-state calibration runs.

1. Vertical permeabilities (leakances) between aquifers under the flood plain of the Rio Grande.
2. Seepage from irrigation.
3. Recharge by underflow through boundaries.
4. Hydraulic conductivity of the shallow aquifer under the flood plain of the Rio Grande.

The final adjusted values are shown in figure 4.

The steady-state analysis indicated that recharge by underflow to the modeled area is about 18,000 acre-ft/yr. Of this, 9,300 acre-ft is recharged to the shallow aquifer, 3,500 acre-ft is recharged to the medium-depth aquifer, and 5,200 acre-ft is recharged to the deep aquifer. The simulations indicated that the net upward leakage from the deep aquifer to the medium-depth aquifer is about 4,700 acre-ft/yr. Net leakage from the medium-depth to the shallow aquifer is about 7,900 acre-ft/yr.

The model also was calibrated in transient state by simulating pumping conditions during 1952-67 and comparing the computed water levels with the observed water-level hydrographs. This period was subdivided into 10 pumping intervals, during each of which, surface-water availability and pumping from all three aquifers were reasonably constant--1952-53, 1954-56, 1957, 1958, 1959-60, 1961-62, 1963, 1964, 1965-66, and 1967. Because water-level data outside the Canutillo well field were unavailable during 1952-67, calibration was necessarily based upon the reproducibility of the hydrographs of observation wells CR-2 and CR-3 in the deep aquifer, CR-5 in the medium-depth aquifer, and CR-1 and CR-4 in the shallow aquifer (fig. 3).

The hydrographs for the wells in the deep, medium-depth, and shallow aquifers, as shown in figure 3, are the annual arithmetic average of the highest daily high-water level and the lowest daily high for each month. The use of highest daily highs and lowest daily highs was necessary because of the large water-level fluctuations within the well field.

The computed water levels in wells CR-2 and CR-3 in the deep aquifer generally are within the range of the annual average of daily high-water levels. The computed water levels for well CR-5 in the medium-depth aquifer generally are above the average annual highs during the early years of development; however, they seem reasonable.

The water levels computed for well CR-1 in the shallow aquifer generally are above the annual average of the highest daily high water levels, whereas those for well CR-4 in the shallow aquifer are within a foot of the average highest daily highs. The high water levels computed for well CR-1 probably reflect the proximity of the well to the constant-head nodes that represent the river.

Further adjustments to the input hydrologic data relative to the shallow aquifer were considered unproductive because (1) the pumpage estimated for the shallow aquifer, other than pumpage by the city of El Paso in the Canutillo well field and pumpage for industrial use in the southern part of the valley, could not be distributed and estimated to a reasonable degree of accuracy; (2) the irrigation drains that traverse the valley were not modeled; (3) the relation between the river and the shallow aquifer was not simulated precisely; and (4) the principal concern of the study was the response to stress in the medium-depth and deep aquifers near the Canutillo well field.

The response of the medium-depth and deep aquifers to continued pumping during 1968-75 was used to further test the model. Pumpage was entered for each of six pumping periods: 1968, 1969-70, 1971, 1972, 1973, and 1974-75. A comparison of the computed water levels with the observed water levels for observation wells CR-2 and CR-3 in the deep aquifer, CR-5 in the medium-depth aquifer, and CR-4 in the shallow aquifer, as shown in figure 3, indicates a reasonable match; but those for well CR-1 in the shallow aquifer were still well above the annual average of the highest daily highs.

## Evaluation of Water-Level Changes Due to Future Development

When the model reasonably reproduced the historic water-level hydrographs in the medium-depth and deep aquifers in the Canutillo well field, it was used to evaluate the water-level changes that would result from (1) a hypothetical increase in pumpage from wells in the Canutillo well field during 1976-80 and (2) a hypothetical lining of the Rio Grande during the same period, at the same pumping rate.

It was assumed that pumping in the Canutillo well field would be increased to 10,000 acre-ft/yr of water out of the medium-depth aquifer and to 20,000 acre-ft/yr of water out of the deep aquifer. Elsewhere, the pumping rate would be maintained at the 1975 rate. The required irrigation water was assumed to be 2 acre-ft per acre per year from surface-water sources and 1 acre-ft per acre per year from ground water, of which 40 percent was assumed to infiltrate back into the shallow aquifer.

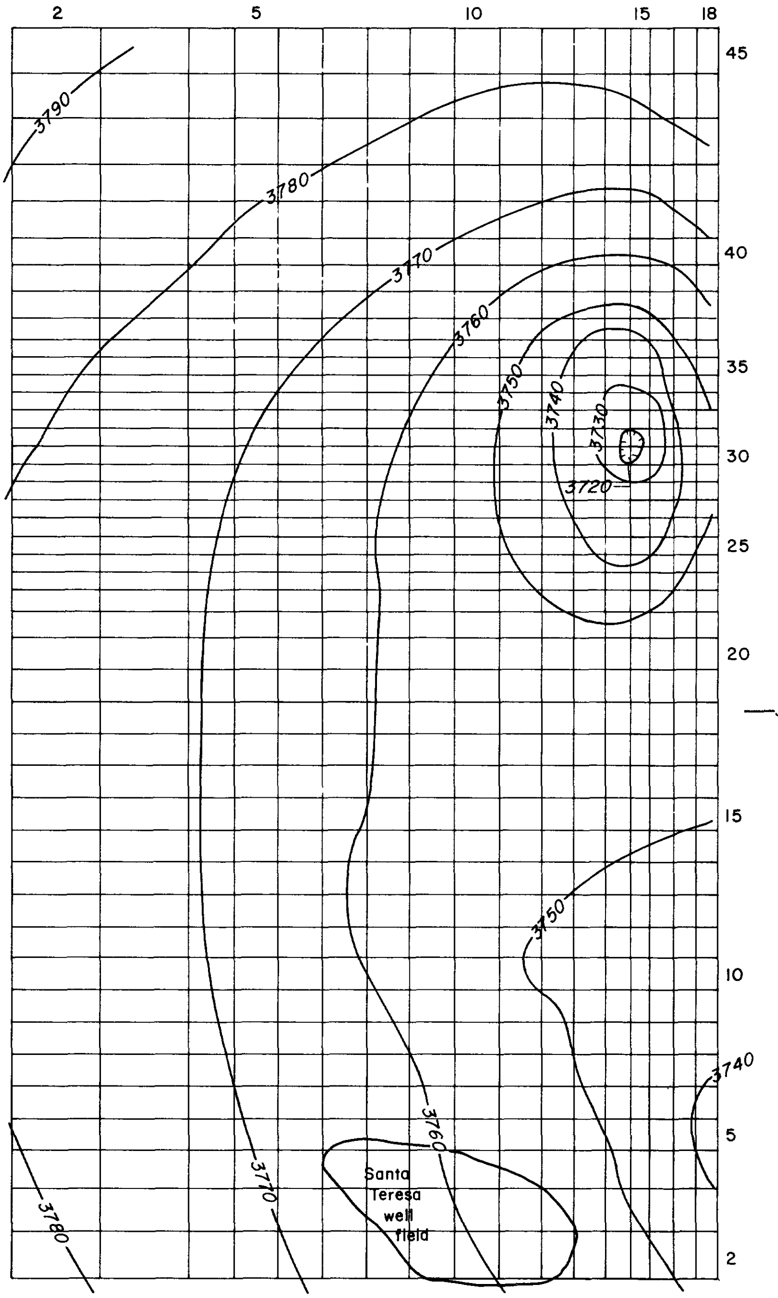
The results shown in figure 3 indicate a sharp decline in water levels in well CR-5 (medium-depth aquifer) and in wells CR-2 and CR-3 (deep aquifer) in the first few months, after which the levels seem to be stabilized. The effect of this simulation was to lower the water levels by as much as 24 ft in well CR-5 in the medium-depth aquifer and 52 feet in well CR-2 in the deep aquifer from the water levels simulated in 1975. Water levels in the shallow aquifer declined about 2 ft.

The model simulations indicate that the additional declines in water levels would result in a substantial increase in the net leakage between aquifers. The net leakage of about 21,000 acre-ft/yr from the shallow to the medium-depth aquifer and about 13,000 acre-ft/yr from the medium-depth to the deep aquifer, equals about two-thirds of the pumpage from the medium-depth and deep aquifers of the Canutillo field.

A substantial part of the leakage from the shallow aquifer probably can be attributed to the high water table that was maintained largely by seepage of irrigation water and water in the Rio Grande. The simulated hydraulic heads in the medium-depth and deep aquifers at the end of 1980 are shown in figures 5 and 6. Figure 6 shows a pronounced cone of depression (lowest altitude, 3,640 ft) in the deep aquifer centered in the Canutillo well field and extending northward to the northern boundary of the modeled area, westward to near the edge of the flood plain, and southward to about 6 mi from the center of the cone.

In the medium-depth aquifer, the cone of depression is broader and shallower than that in the deep aquifer. The pumping of about 2,000 acre-ft/yr in the Santa Teresa well field in the southwestern part of the modeled area (fig. 2) did not create a cone of depression and probably had no significant effects on water levels in or near the Canutillo well field.

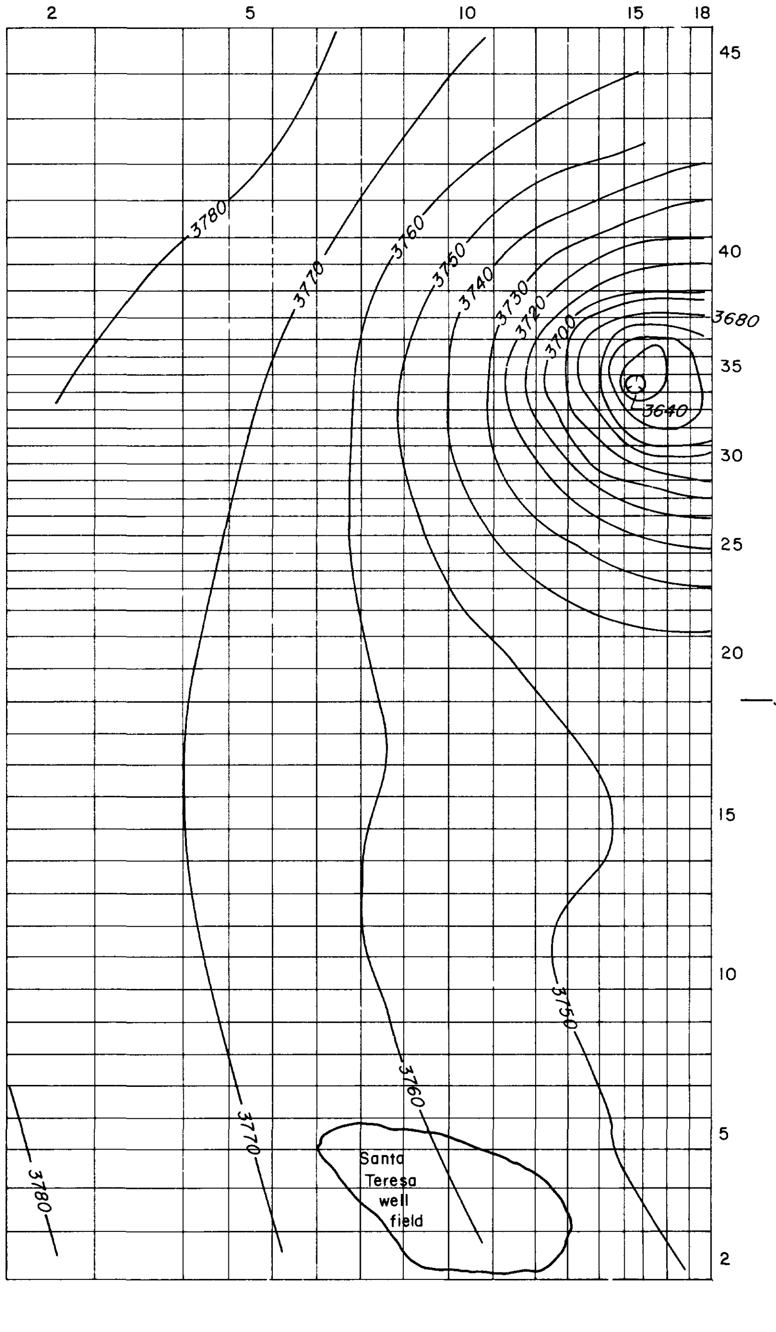
The model also was used to determine the effects on water levels in the medium-depth and deep aquifers of a hypothetical plan in which the entire flow of the Rio Grande in the modeled area would be enclosed in a concrete channel during 1976-80. Assuming the same pumping rate of 10,000 acre-ft/yr of water out of the medium-depth aquifer and 20,000 acre-ft/yr of water out of the deep aquifer and elsewhere the pumping rate was held constant, then water levels




EXPLANATION

—3760— WATER-LEVEL CONTOUR -- Shows approximate altitude of water level for the medium-depth aquifer as computed by the model. Contour interval 10 feet. Datum is sea level

FIGURE 5.-Approximate water-level contours for the medium-depth aquifer in December 1980, as computed by the model




## EXPLANATION

—3760— WATER-LEVEL CONTOUR-- Shows approximate altitude of water level for the deep aquifer as computed by the model. Contour interval 10 feet. Datum is sea level

**FIGURE 6.-Approximate water-level contours for the deep aquifer in December 1980, as computed by the model**

would be lowered an additional 10 ft in well CR-5 in the medium-depth aquifer and 8 ft in well CR-2 in the deep aquifer.

The channel lining was simulated by removing the constant-head nodes which represented the Rio Grande and by eliminating the irrigation infiltration from these nodes so that "channel-lined" and "channel-unlined" simulations would be comparable. Under this condition, no water would be released from the Rio Grande except the water stored in the aquifer materials under the river bed.

The impact of potential development of water from the medium-depth and deep aquifers for irrigation was not evaluated by the simulations. However, on the basis of the simulation results of increased pumping by the city of El Paso, additional withdrawals for irrigation of about 30,000 acre-ft/yr from the medium-depth and deep aquifers in the northern part of the valley, where water quality is good, probably would result in substantial water-level declines in both aquifers.

## DISCUSSION

The authors realize that the simulation model includes an error and has several deficiencies and believe that the simulation results need to be interpreted carefully. The error in the model and its deficiencies are:

1. No geologic evidence is available indicating that extensive confining beds exist in the area beyond the flood plain, and the entire section (including lateral equivalents of the shallow, medium-depth, and deep aquifers) may form one unit under water-table conditions. However, a permeability contrast between the horizontal direction and vertical direction probably exists. For this reason, the simulation model has leakance values of $25 \times 10^{-9}$ and $15 \times 10^{-9}$ for the lateral equivalents of the medium-depth and deep aquifers, respectively. Because of this permeability contrast, water stored in the lateral equivalents of the medium-depth and deep aquifers in the area outside of the flood plain is under pressure rather than under atmospheric conditions even if the three aquifers are hydraulically connected without evidence of confining beds. In addition, even without a horizontal-vertical permeability contrast, water can be removed from storage (when a water-table storage coefficient or specific yield is appropriate) only at the upper surface of the unit. The value of 0.10, assigned as specific yield in the simulation model for the lateral equivalents of both the medium-depth and deep aquifers for the area outside of the flood plain, is in error. An artesian coefficient of storage of the same value, $7 \times 10^{-4}$, used for the medium-depth and deep aquifers under the flood plain, probably is the appropriate value to be used in the simulation. However, this error was discovered during the report writing, and time was not available to revise and rerun the model. This error probably results in release of too much water from storage in the area outside of the flood plain when the cone of depression reaches that part of the area, further resulting in a change in water levels that is too small. If this simulation model is refined in the future, this error needs to be corrected.

2. The Rio Grande probably cuts into the shallow aquifer less than 20 ft. Using constant-head nodes in the shallow aquifer was not the best way to simulate the Rio Grande. A better method to simulate the Rio Grande would have

been to use the river-node simulation technique instead of constant-head nodes. However, this option was not available for the three-dimensional model when this study was done, and the study objective was to simulate the medium-depth and deep aquifers, with only an approximate simulation of the shallow aquifer.

3. The cone of depression reached the western and northern boundaries of the model during transient-state simulations. The values of underflow through boundaries were calculated by Darcy's law on the basis of estimated hydraulic gradients and hydraulic conductivity near the boundaries. When an actual cone of depression reaches the distance equal to a boundary, it will change the hydraulic gradient, and thus, indirectly change the underflow rate. However, this will increase the underflow rate rather than decrease it if enough water is available beyond the boundary (which is the case in the study area). Thus, this model deficiency probably yields a conservative result in that simulated water-level declines would be larger than actual changes. However, to better simulate the system, the modeled area needs to be extended farther west and north beyond the limits of the cone of depression during transient-state simulation.

4. More data, especially water-level measurements, need to be collected in the area beyond the Canutillo well field. The accuracy of a simulation model depends on the calibration of the simulated water levels against observed water levels. A better distribution of water-level information would yield a better simulation model. However, because few wells exist outside the flood plain of the Rio Grande, observation wells would have to be drilled to provide a good distribution of water-level data.

Because of the above discussed deficiencies, the authors believe that the simulation results could be used best as a preliminary and conceptual evaluation of the effects of pumping at the Canutillo well field, not as a quantitative interpretation. Although the patterns of simulated hydrographs of water-level change in observation wells in the Canutillo well field generally may be correct, the amount of change simulated probably may not be correct.

Because of the increased salinity of water in all three aquifers south of Canutillo, it is probable that this more-saline water may move north toward the Canutillo well field if the cone of depression reaches that part of the aquifer. This problem should be evaluated in future studies.

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