EVALUATION OF PROPOSED WATER-MANAGEMENT ALTERNATIVES TO LOWER THE HIGH WATER TABLE IN THE ARKANSAS RIVER VALLEY NEAR LA JUNTA, COLORADO

by K.R. Watts and J.B. Lindner-Lunsford

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 91-4046

Prepared in cooperation with the

NORTH LA JUNTA WATER CONSERVANCY DISTRICT

Denver, Colorado
1992

U.S. DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Box 25046, Mail Stop 415
Federal Center
Denver, CO 80225-0046

Copies of this report can
be purchased from:

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

CONTENTS

FIGURES

TABLES

GLOSSARY

aquifer.--A permeable water-bearing body of earth material that yields water in usable quantities to wells and springs.

bedrock.--The consolidated rock that underlies the soil and other unconsolidated earth materials at the land surface.

calibration.--The process of systematically adjusting model input to produce simulated results that match observed phenomena. In practice, model input is adjusted within limits based on the reliability of the data until simulated output match observed phenomena within some predetermined range of error.

conductance.--The combination of several parameters used in Darcy's law. Conductance (C) is defined as C = KA/L, where K is the hydraulic conductivity of the aquifer in the direction of flow; A is the cross-sectional area perpendicular to the flow; and L is the length of the flow path (McDonald and Harbaugh, 1988, p. 5-2).

drawdown.--The decrease in the potentiometric surface at a point caused by the withdrawal of water from an aquifer.

ground-water budget.--An arithmetic expression of the quantities of water entering or leaving the ground-water system from all sources including the change in the quantity of water in storage.

head.--height above a standard datum, commonly sea level, of the surface of a column of water that can be supported by the pressure at a given point. Static head is the sum of elevation head and pressure head. Total head also includes velocity head (Lohman and others, 1972, p. 7).

hydraulic conductivity.--A measure of the ability of an aquifer material to transmit water. It is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (Lohman and others, 1972, p. 4).

hydraulic gradient.--The change in static head per unit of distance in a given direction that generally is measured in the direction of maximum decrease in head (Lohman and others, 1972, p. 8).

leakage.--The rate of flow between two bodies of water (surface and ground water) through a permeable membrane (canal or riverbed).

sensitivity.--Extent to which model output is affected by changes in model input, such as the rate of ground-water pumpage.

specific yield.--A measure of the ability of an unconfined aquifer to yield water. It is the ratio of (1) the volume of water which the rock or soil, after being saturated, will yield by gravity to (2) the volume of the rock or soil (Lohman and others, 1972, p. 12).

steady state.--A state of dynamic equilibrium in which the quantity of water entering the system is constant and is exactly balanced by water leaving the system. Because recharge equals discharge, no change in storage occurs and water levels are steady.

transmissivity.--The rate at which water at the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman and others, 1972, p. 13).

underflow.--Water that moves beneath the land's surface.

water table.--The water surface in an unconfined water body at which the pressure is atmospheric (Lohman and others, 1972, p. 14).

CONVERSION FACTORS

Multiply	*By*	*To obtain*
acre	0.40469	hectare meter
acre-foot (acre-ft)	1,233.4	cubic meter
acre-foot per year (acre-ft/yr)	1,233.4	cubic meter per year
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per mile [(ft^3/s)/mi]	0.01760	cubic meter per second per kilometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.18943	meter per kilometer
foot per year (ft/yr)	0.3048	meter per year
gallon per day (gal/d)	0.003785	cubic meter per day
gallon per minute (gal/min)	0.06308	liter per second
inch (in.)	25.40	millimeter
mile (mi)	1.609	kilometer
square foot per day (ft^2/d)	0.09290	square meter per day
square mile (mi^2)	2.590	square kilometer

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A Geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

The following terms and abbreviations also are used in this report:

second per day (s/d)
day per year (d/yr)
square foot per acre (ft^2/acre)

EVALUATION OF PROPOSED WATER-MANAGEMENT ALTERNATIVES TO LOWER THE HIGH WATER TABLE IN THE ARKANSAS RIVER VALLEY NEAR LA JUNTA, COLORADO

By K.R. Watts and J.B. Lindner-Lunsford

ABSTRACT

The water table in the alluvial aquifer near La Junta, Colorado, rose during the 1980's in response to changes in rates of recharge and discharge--primarily leakage from the Arkansas River and Fort Lyon Canal and ground-water pumpage. Aggradation of the bed of the Arkansas River also contributed to the rise of the water table. Five water-management alternatives that were proposed as methods of lowering the water table in the valley are: (1) Deepening the channel of the Arkansas River, (2) lining the Fort Lyon Canal, (3) increasing municipal pumpage, (4) installing relief wells, and (5) installing a drainage system.

A numerical model of steady-state ground-water flow was used to test the sensitivity of the system to errors in the estimates of hydraulic properties and recharge and discharge conditions. The model was sensitive to the simulated altitude of the riverbed, pumpage rates, conductance of the beds of the Arkansas River and Fort Lyon Canal, areal recharge rates, and evapotranspiration, but only moderately sensitive to values of hydraulic conductivity. The model was calibrated to April 1960-December 1984 transient conditions and used to evaluate the potential hydrologic effects of the proposed water-management alternatives for 1985-86 transient conditions.

A simulated deepening of the channel of the Arkansas River by 4 feet caused about a 4-foot decrease in simulated heads in most of the area. Simulated lining of the Fort Lyon Canal caused about a 5-foot decrease in simulated heads near the canal, almost no change in heads near the river, and increased leakage from the river. Increasing simulated municipal pumpage caused localized decreases in simulated head and also increased leakage from the river. The simulated relief wells and simulated drainage system locally decreased simulated heads and substantially increased leakage from the river.

INTRODUCTION

The alluvial aquifer underlying the flood plain of the Arkansas River near La Junta, Colorado (fig. 1), is a highly transmissive unconfined aquifer. The Arkansas River partially penetrates the aquifer and may act as either a drain or a source of water to the aquifer depending on the relative altitude of the water table and the stage of the river. The water table in the alluvial aquifer that underlies the Arkansas River valley in the La Junta, Colorado, area rose during the early 1980's in response to changes in rates of recharge and discharge to the aquifer--primarily increased leakage from the Arkansas River and Fort Lyon Canal and decreased ground-water pumpage.

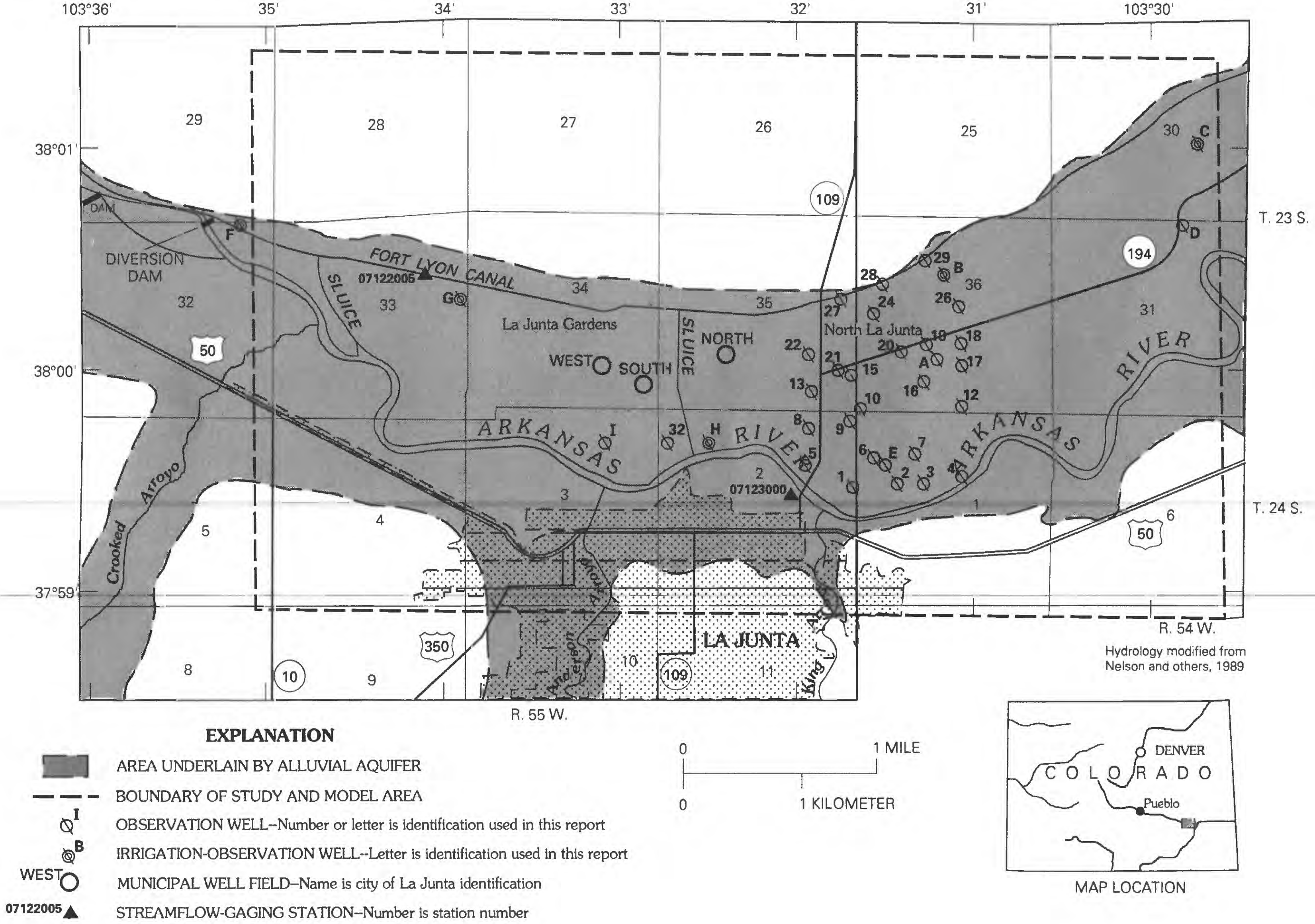

Figure 1.--Location of the study and model areas and selected wells.

However, the relative importance of these factors is not known. The change in depth to the water table has caused flooding of basements, loss of some productive farmland, and the closure of a public school. Several water-management alternatives have been proposed by the North La Junta Water Conservancy District to lower the high water table in the La Junta area: (1) Deepening the channel of the Arkansas River, (2) lining the Fort Lyon Canal, (3) increasing municipal pumpage, (4) installing relief wells, and (5) installing a drainage system. The effectiveness of the proposed methods of lowering the water table needed to be quantitatively evaluated so that an effective means of lowering the high water table could be implemented.

In the fall of 1985, the North La Junta Water Conservancy District requested that the U.S. Geological Survey conduct a hydrologic study to determine the cause of the high water-table conditions in the alluvial aquifer of the Arkansas River valley near La Junta and to evaluate the potential hydrologic effects of five water-management alternatives that had been proposed as means of lowering the water table. During 1986-87, a study was conducted to: (1) Quantify sources of ground-water inflow and outflow in the area, (2) determine direction of ground-water flow, and (3) investigate the sensitivity of the hydrologic system to changes in the quantities of inflow or outflow. A ground-water model was developed to verify the conceptualization of the hydrologic system and as an aid to evaluate potential effects of the water-management alternatives. Economic, legal, and practical aspects involved in implementing the alternatives were not considered in the study, which dealt only with evaluating the responses of the hydrologic system to the changes in stresses.

Purpose and Scope

This report describes the results of a 1-year study of the alluvial aquifer in the Arkansas River valley near La Junta, Colorado, which was begun in 1986 to evaluate the potential hydrologic effects of five water-management alternatives that had been proposed as methods of lowering the high water table. Published reports, previously completed data-collection programs and hydrologic studies, and data collected during this study were used to quantify sources of ground-water inflow and outflow in the area, to develop an estimated ground-water budget, and to calibrate a numerical model of ground-water flow.

Water levels were measured weekly during 1986 in an existing observation-well network in North La Junta. Additional observation wells and replacement wells were installed during the summer of 1986. A gain-loss investigation of the Fort Lyon Canal in the study area was done on November 13, 1986.

A ground-water budget was estimated for average annual conditions during the 1960-79 period. This budget and geohydrologic data served as the conceptual model used in developing a numerical model for average 1960-79 (steady-state) conditions. Steady-state conditions were assumed because there were no persistent (long-term) changes in water levels, streamflow conditions, and irrigation diversions during 1960-79. The numerical model for steady-state conditions was used to test the sensitivity of the conceptual model to errors in the estimated values of hydraulic properties and recharge and discharge conditions.

The numerical model then was calibrated to simulate monthly transient conditions for the April 1960-December 1984 period. The numerical model, calibrated for transient model conditions, then was used to simulate the hypothetical hydrologic effects of the five proposed water-management alternatives for 1985-86 monthly conditions. Simulated ground-water budgets and maps of simulated depth to water and water-level change were used to evaluate the water-management alternatives.

Description of the Study Area

The study area (fig. 1) consists of a 5-mi-long section of the Arkansas River valley near La Junta, Colorado. The alluvial aquifer in the study area is about 1.5 mi wide and about 7.6 mi^2 (4,874 acres) in extent. Two small unincorporated communities, North La Junta and La Junta Gardens, are located within the area underlain by the alluvial aquifer and within which land use is primarily agricultural.

The land surface in the valley is relatively flat and most of the valley is within the flood plain of the Arkansas River (U.S. Army Corps of Engineers, 1977). The altitude of the land surface within the valley ranges from about 4,020 to 4,090 ft above sea level; local relief between the valley floor and nearby upland areas is about 100 to 150 ft.

The climate of the area is semiarid. Annual precipitation averages about 11 in. (National Oceanic and Atmospheric Administration, 1986). Most of the precipitation occurs during the growing season, April-September. Seasonal pan evaporation during April-October averages about 59 in. (Weist, 1965). Because the potential evaporation, as indicated by pan evaporation, is larger than precipitation during the growing season, irrigation of crops is needed.

Surface and ground water are used to irrigate about 2,100 acres in the study area underlain by the alluvial aquifer (Konikow and Bredehoeft, 1973, fig. 15). Nonirrigated area underlain by the alluvial aquifer is about 2,774 acres. Although surface water is the primary source of irrigation water in the study area, when the surface-water supply is insufficient to meet demand, or it is being diverted for use downstream from the study area, ground water is used for supplemental irrigation water. Surface water from the Arkansas River is diverted upstream from the study area (fig. 1) by the Fort Lyon Canal for irrigation of about 91,300 acres in southeastern Colorado, including 2,100 acres in the study area. Water levels are measured in selected irrigation wells as part of on-going data-collection networks; those wells are shown as irrigation-observation wells in figure 1. Forty-one irrigation wells, three municipal well fields (there were four municipal well fields, but one well field is no longer used), and one industrial well (fig. 1) withdraw ground water from the alluvial aquifer in the study area.

The Arkansas River, a perennial stream with a shifting sand channel, crosses the study area from west to east--mainly along the south side of the valley. Discharge of the river is measured near the center of the study area at streamflow-gaging station 07123000 (fig. 1). Flow in the river is affected by diversions of surface and ground water, irrigation return flows, and reservoirs.

The Fort Lyon Canal crosses the study area along the north side of the valley. Diversions by the canal are measured in a 40-ft Parshall flume at gaging station 07122005 (fig. 1). Because of the low gradient and consequent slow velocities in the canal, sediment in water diverted from the river is deposited in the canal. Often, the entire flow of the river is diverted by the Fort Lyon Canal. Two sluices (fig. 1) are used to control aggradation in the canal upstream and downstream from the measuring flume. The operation of the sand sluices increases the sediment load that must be carried by the river downstream from the Fort Lyon Canal diversion dam. Water levels in sumps of residences near the sluices reportedly rise soon after the sluices begin to flow (Mark Korbitz, North La Junta Water Conservancy District, oral commun., 1986). Because the sluices are unlined, they act as line sources of recharge to the alluvial aquifer.

Acknowledgments

The authors gratefully acknowledge the cooperation of Mr. Roy Fritch, advisor to, and the members of the La Junta High School Science Club, who measured water levels in the observation-well network during 1986-87; Mr. Harold Scofield, Director of Public Works, city of La Junta, who provided municipal pumpage records; Mr. Rick Klein, Otero County Engineer, who provided historical water-level data; Mr. Ron Callahan, Superintendent of the Fort Lyon Canal Company, who permitted access to the canal for gain-loss measurements; Irrigation Division 2 Engineer's Office, Colorado Department of Water Resources, which provided discharge and diversion data; and the Albuquerque District of U.S. Army Corps of Engineers, which provided copies of drillers' logs of observation wells. The cooperation of local property owners, who allowed access to observation wells on private property also is acknowledged.

GEOHYDROLOGIC SETTING

The alluvial aquifer in the study area is a relatively thin, unconfined aquifer. Saturated thickness in 1966 was less than about 35 ft (fig. 2, after Nelson and others, 1989, sheet 2), but the aquifer is highly transmissive. The aquifer is hydraulically connected to the Arkansas River, which is a partially penetrating stream. Sources of recharge to the aquifer in the study area are leakage from the Arkansas River and the Fort Lyon Canal, deep percolation of irrigation water and precipitation, and underflow. Discharges from the aquifer are leakage to the Arkansas River; pumpage for municipal, irrigation, and industrial supplies; evapotranspiration; and underflow.

The alluvial aquifer in the study area consists of Holocene and Pleistocene alluvial deposits that consist of clay, silt, sand, and gravel with some cobbles and boulders (Weist, 1965). These unconsolidated sediments were deposited in an erosional trough in relatively impermeable Upper Cretaceous limestone and shale (bedrock). The altitude and configuration of the bedrock surface is shown in figure 3. Although numerous faults with small vertical displacements have been mapped in the bedrock exposed in the uplands adjacent to the valley (Weist, 1965, pl. 1), these faults are not believed to substantially affect ground-water flow between the alluvial aquifer and underlying bedrock.

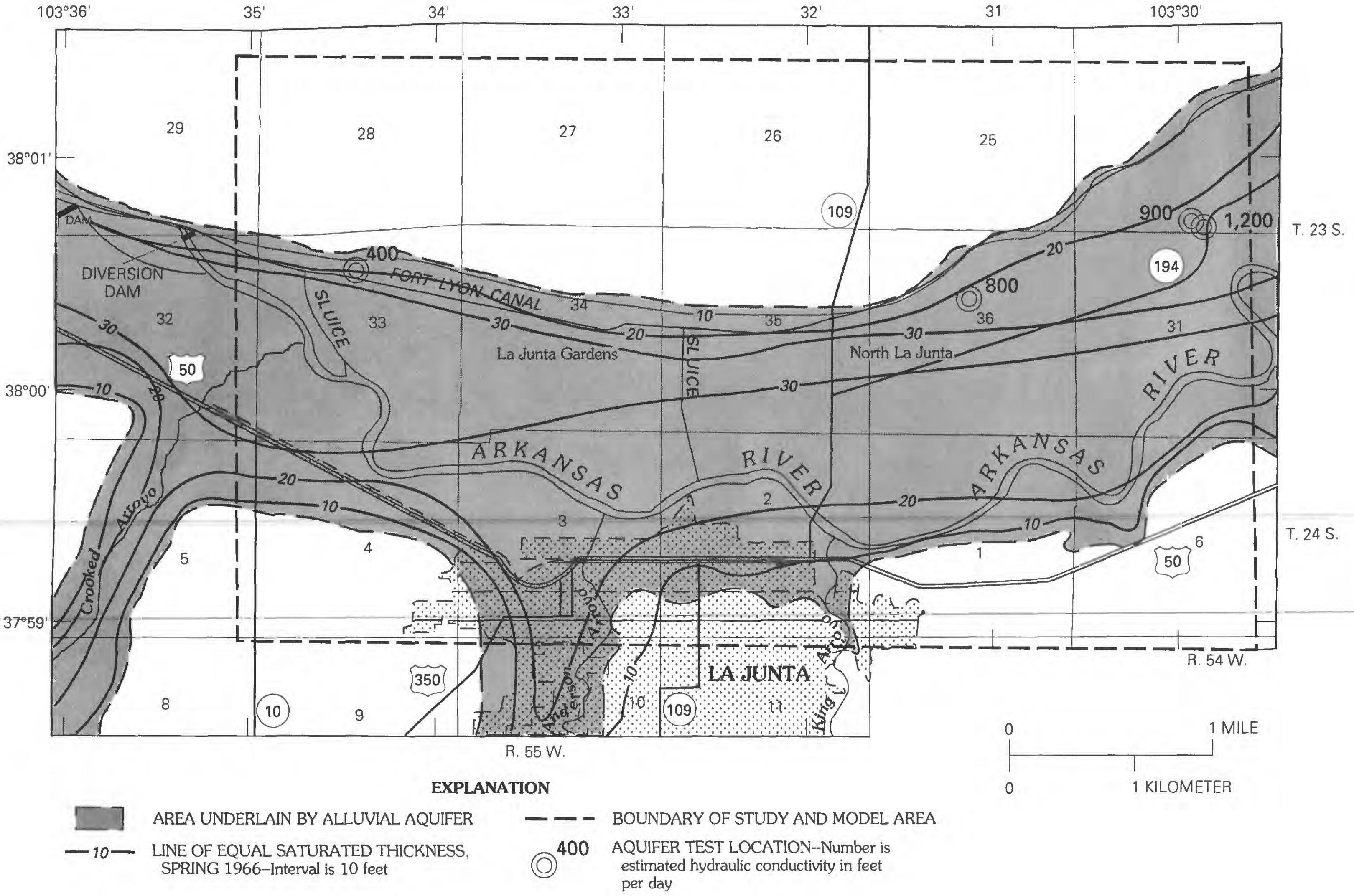

Figure 2.--Saturated thickness and estimated hydraulic-conductivity values of the alluvial aquifer in spring 1966.

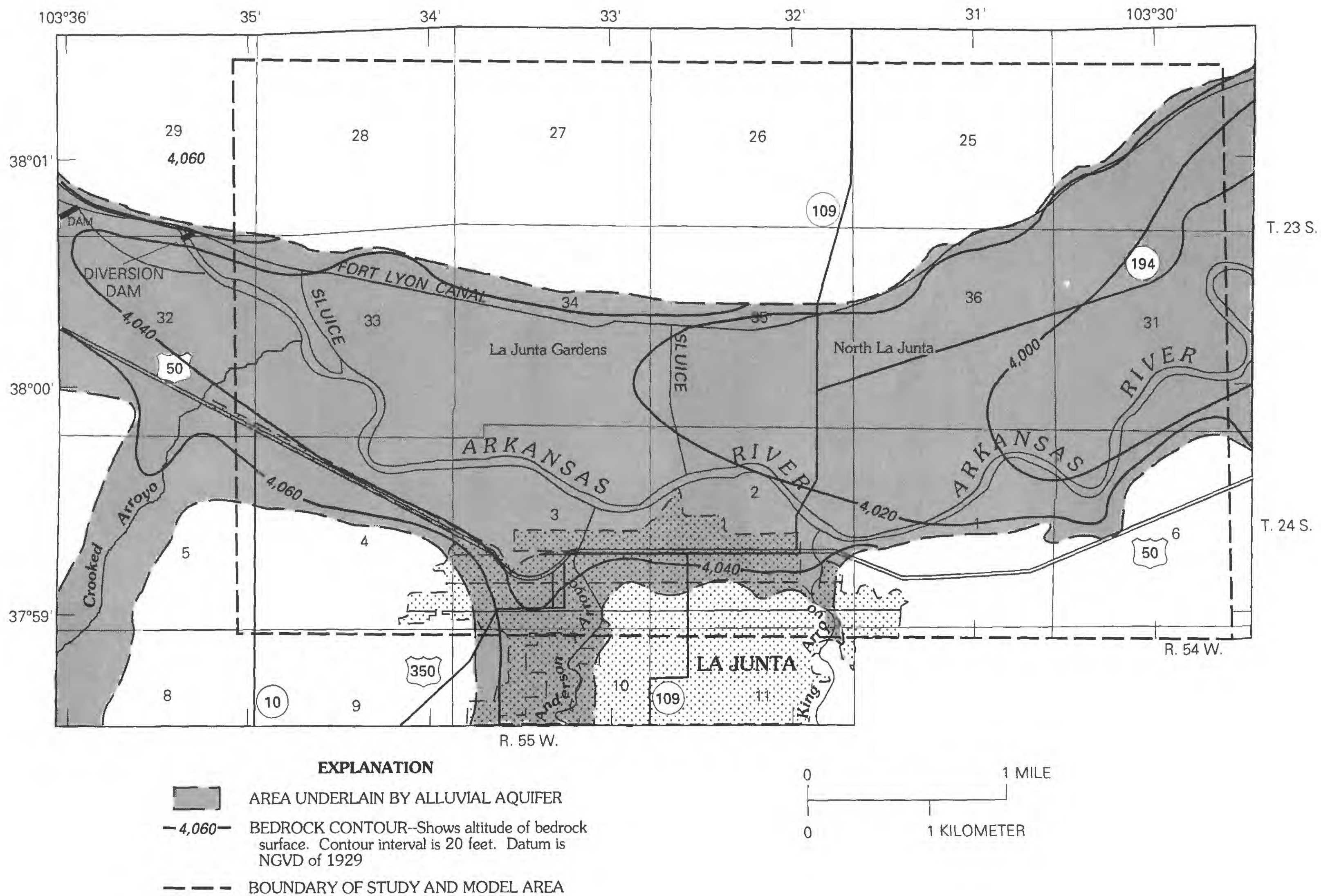

Figure 3.--Generalized altitude and configuration of the bedrock surface.

Hydraulic Characteristics

The hydraulic-conductivity values of the saturated alluvial deposits, as determined by aquifer tests (Weist, 1965, table 4), range from about 400 to 1,200 ft/d (fig. 2). The average value of hydraulic conductivity (K) of the alluvial aquifer was estimated to be about 670 ft/d by dividing the estimated transmissivity (T) of the alluvial aquifer (Moore and Wood, 1967, fig. 7) by the spring 1966 saturated thickness (b) (Nelson and others, 1989, sheet 3). Locally, the heterogeneity of the alluvium may cause anisotropy in the alluvial aquifer; however, the alluvial aquifer is considered to be homogeneous and isotropic for larger areas. The estimated value of specific yield of the alluvial aquifer, as determined from neutron-moisture data (Weeks and Sorey, 1973) and aquifer tests (Weist, 1965, table 4), range from 0.17 to 0.25. Konikow and Bredehoeft (1973) used a specific yield of 0.20 in their numerical model of the alluvial aquifer in the Arkansas River valley from approximately Crooked Arroyo to the Bent-Otero County line, an area which includes most of the valley in the study area for this report but which extends about 6 mi farther east.

Response of the Water Table to Variations in Recharge and Discharge

Seasonal and long-term fluctuations of the water table are controlled by seasonal and long-term variations in the rates of recharge and discharge of the aquifer. Water-level hydrographs (fig. 4) of nine wells (fig. 1; wells A-I) indicate that prior to 1980, water levels varied seasonly but were relatively stable from year to year. This relative stability of water levels indicates that recharge-discharge conditions were in a steady-state condition. Storage in the aquifer, as indicated by most of the hydrographs (fig. 4) increased only slightly during the 1960's and 1970's. The hydrograph (fig. 4) for well G (fig. 1) indicates a relatively stable seasonal fluctuation until 1976, when the range of seasonal fluctuations increased from about 2 ft to as much as 11 ft. Although the seasonal lows during 1976-84 were at about the same levels as during 1965-75, the seasonal highs increased steadily. Well G is located in an irrigated area and is relatively near the Fort Lyon Canal. Changes in the timing and rates of diversion of surface water for irrigation and a consequent reduction in ground-water pumpage for irrigation probably resulted in a net increase in recharge to the aquifer at this site. The seasonal highs at well G occurred during the summer months, when surface-water diversions for irrigation were greatest. The hydrographs (fig. 4), which are also for wells--wells B and F (fig. 1)--located in irrigated areas near the Fort Lyon Canal, are based only on annual (mid-winter) measurements and, therefore, do not exhibit seasonal fluctuations.

The hydrograph (fig. 4) for well D (fig. 1), which is also in an irrigated area but relatively close to the Arkansas River, showed a relatively steady increase in water levels during the 1980's of about 1 ft/yr. Seasonal highs at well D during the 1980's also occurred during the summer, when stages in both the Fort Lyon Canal and Arkansas River were high in relation to stages during the 1970's. Unlike the water table at well G during the 1980's, seasonal lows for the water table at well D also increased at about the same rate as the seasonal highs. The water table at well D primarily was affected by relatively high stages in the river.

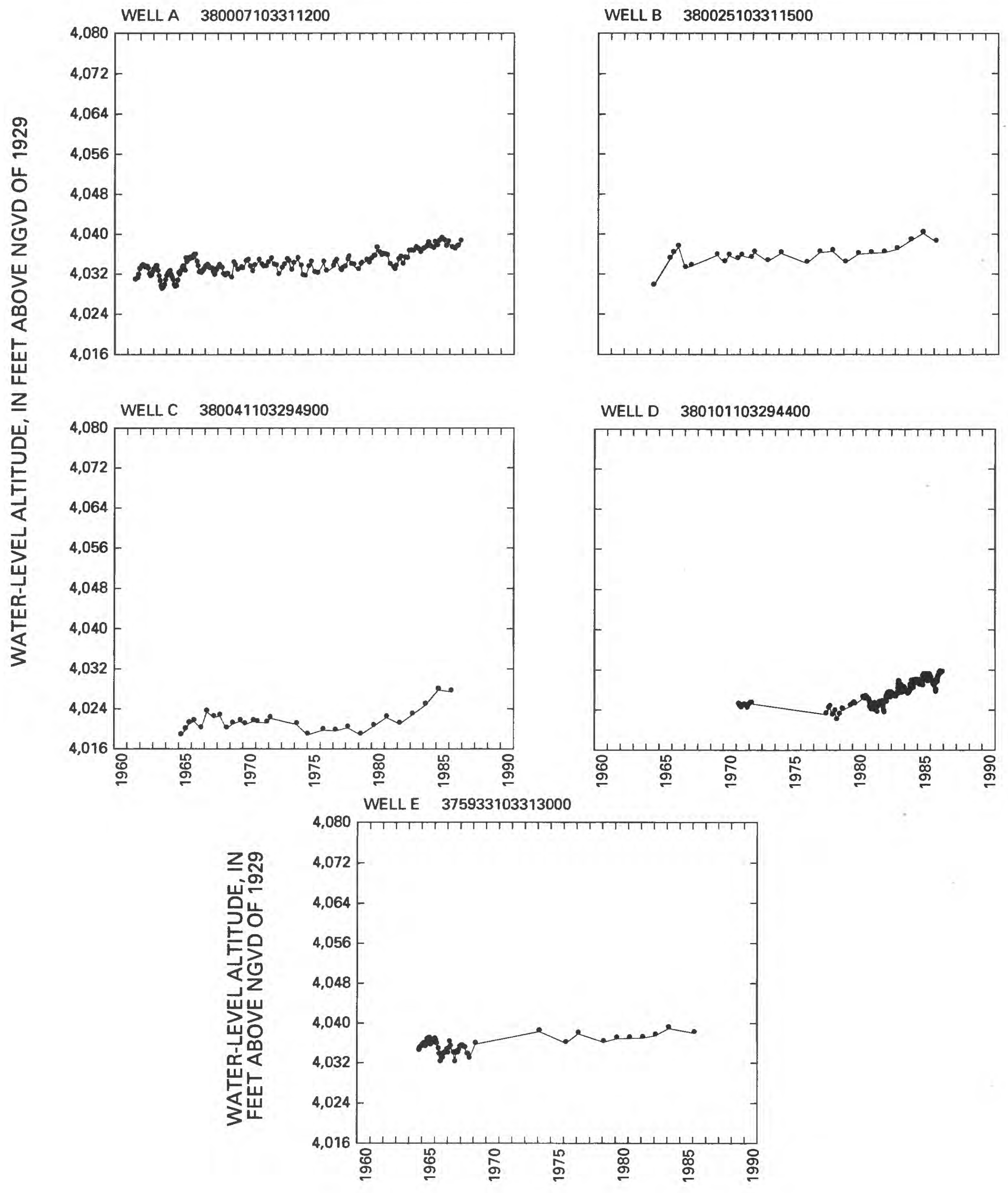

Figure 4.--Water-level altitudes in the alluvial aquifer, 1960-86. The 15-digit number following the well designation is the U.S. Geological Survey site-identification number. The lines connecting data points do not infer intermediate values and only are shown to indicate trends.

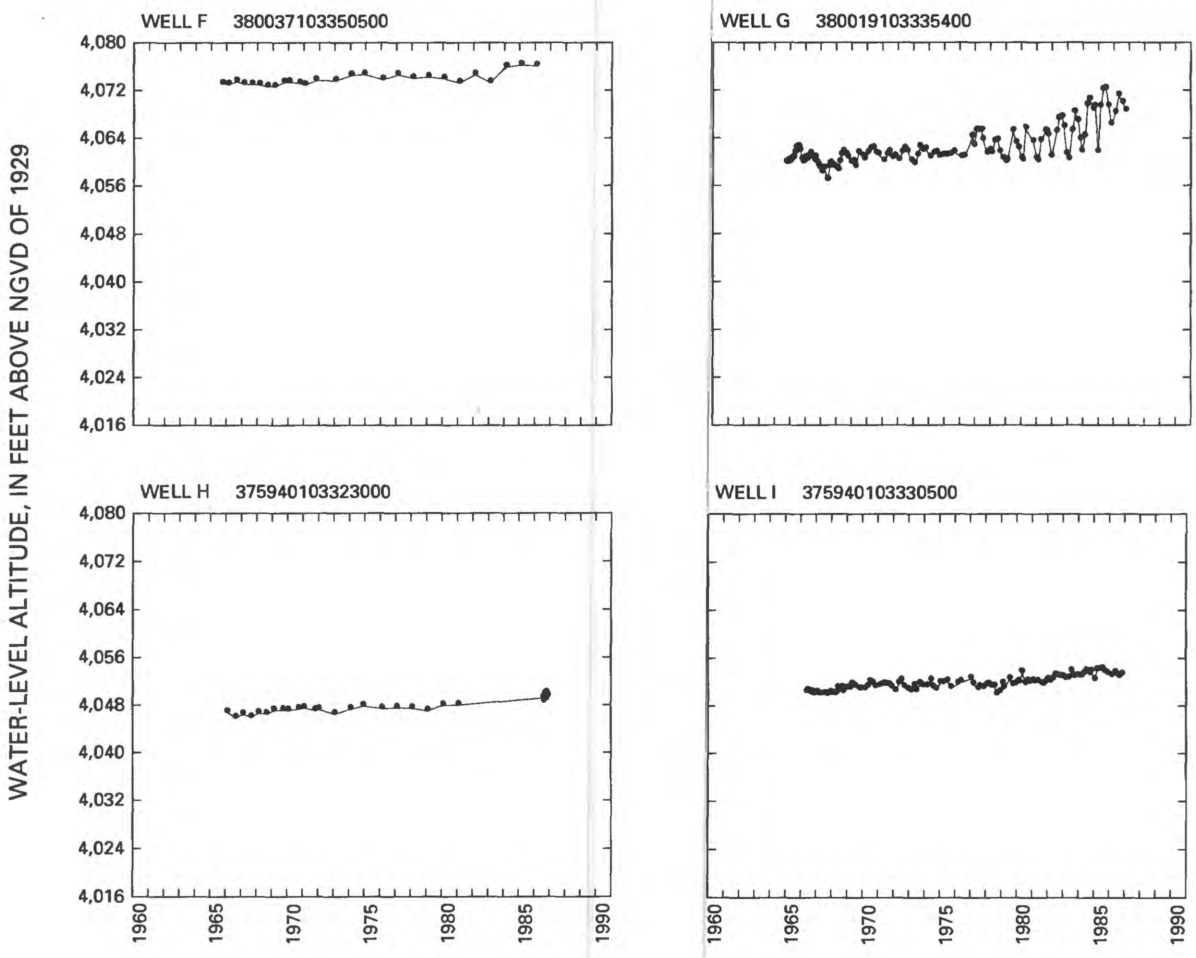

Figure 4.--Water-level altitudes in the alluvial aquifer, 1960-86. The 15-digit number following the well designation is the U.S. Geological Survey site-identification number. The lines connecting data points do not infer intermediate values and only are shown to indicate trends--Continued.

The rise in water levels after about 1979 indicates that recharge increased relative to discharge. Water levels in wells near the Fort Lyon Canal and in irrigated areas had larger changes than water levels in wells near the river. The water-level change probably has resulted from a combination of factors: Increased surface-water infiltration, increased seepage losses from the canal, decreased ground-water pumpage, and increased percolation of irrigation water to the water table.

Hydrographs of the depth to water in observation wells in North La Junta (fig. 1) during 1984-87 indicate that water levels were near land surface in much of the area (fig. 29 in the "Supplemental Information" section at the back of the report). Land-surface datum for the observation wells, used for figure 29, were interpolated from topographic maps (U.S. Army Corps of Engineers, 1977, plates 5-15). Two observation wells, well 1 and well 20, are located on manmade features--well 1 is located on a levee about 7 ft higher than the adjacent area, and well 20 is located in a 4½-ft deep irrigation lateral.

The slope of the water-table surface during April 1960 was generally to the east, but locally was towards the river (fig. 5, modified from Weist, 1965, pl. 2). Because data were not available, contours of the water-table altitude near the river in figure 5 are only approximately located. As drawn, the contours indicate a gaining reach during April 1960. Maps of the water-table surface during spring 1966 (Nelson and others, 1989, sheet 1) and March 1, 1971, and March 1, 1972 (Konikow and Bredehoeft, 1973, figs. 7 and 17), show similar configurations of the water table. These maps of the water table were based on measurements made when the river stage was at a seasonal low and when there was little ground-water pumpage for irrigation; therefore, the hydraulic gradient was from the aquifer to the river. During the summer, when there is increased ground-water pumpage for municipal and irrigation supply, locally, the hydraulic gradient is reversed, and flow is from the river to the aquifer.

Moore and Wood (1967, p. 22) state, "In May, before much ground-water pumping, the river between the Fort Lyon Diversion Dam (near La Junta) and a point near the county line had a net loss of 7 cfs (cubic feet per second).... In July, the period of greatest pumping, the river between the same points had a net loss of 37 cfs....The areas of greatest loss correspond closely to areas of greatest decline of water level and to areas of greatest withdrawal of ground water...."

Stream-Aquifer Interaction and Streambed Conductance and Leakance

The rate and direction of flow between the Arkansas River and the aquifer is a function of the hydraulic gradient between the water table and the stage of the river, and the conductance of the riverbed-aquifer interface. The hydraulic gradient varies with changes in altitude of the water table and stage in the river. The water-table map (fig. 5) was based on water-level measurements made during April 1960, when monthly mean discharge of the Arkansas River at La Junta was only 44.7 ft^3/s. This discharge corresponds to a stream stage of about 0.4 ft above the riverbed, based on the rating table for 1960 (Hendricks, 1962, p. 125). The stage of the river is a function of streamflow and channel geometry. Monthly mean discharge of the Arkansas River at La Junta (station 07123000) (fig. 6) during 1960-86 ranged from 4.2 to 2,913 ft^3/s. Instantaneous discharge during 1960-86 ranged from 0 to 31,700 ft^3/s. Changes in the channel geometry will cause a change in the stage for a given discharge. Streamflow at La Junta is affected by upstream diversions by the Fort Lyon Canal and operations of two sluices to control sedimentation in the canal.

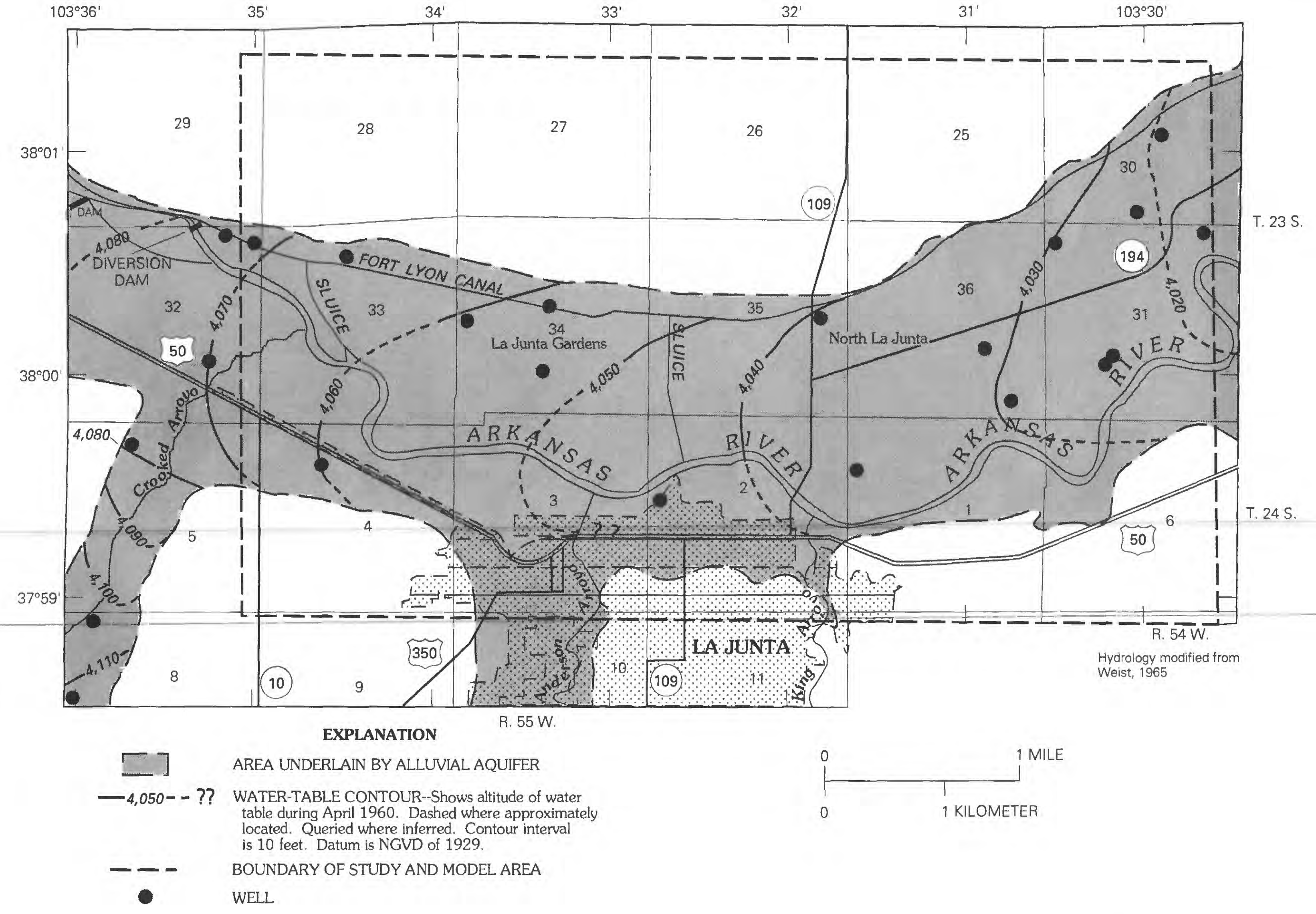

Figure 5.--Generalized altitude and configuration of the water table, April 1960 (modified from Weist, 1965, pl. 2).

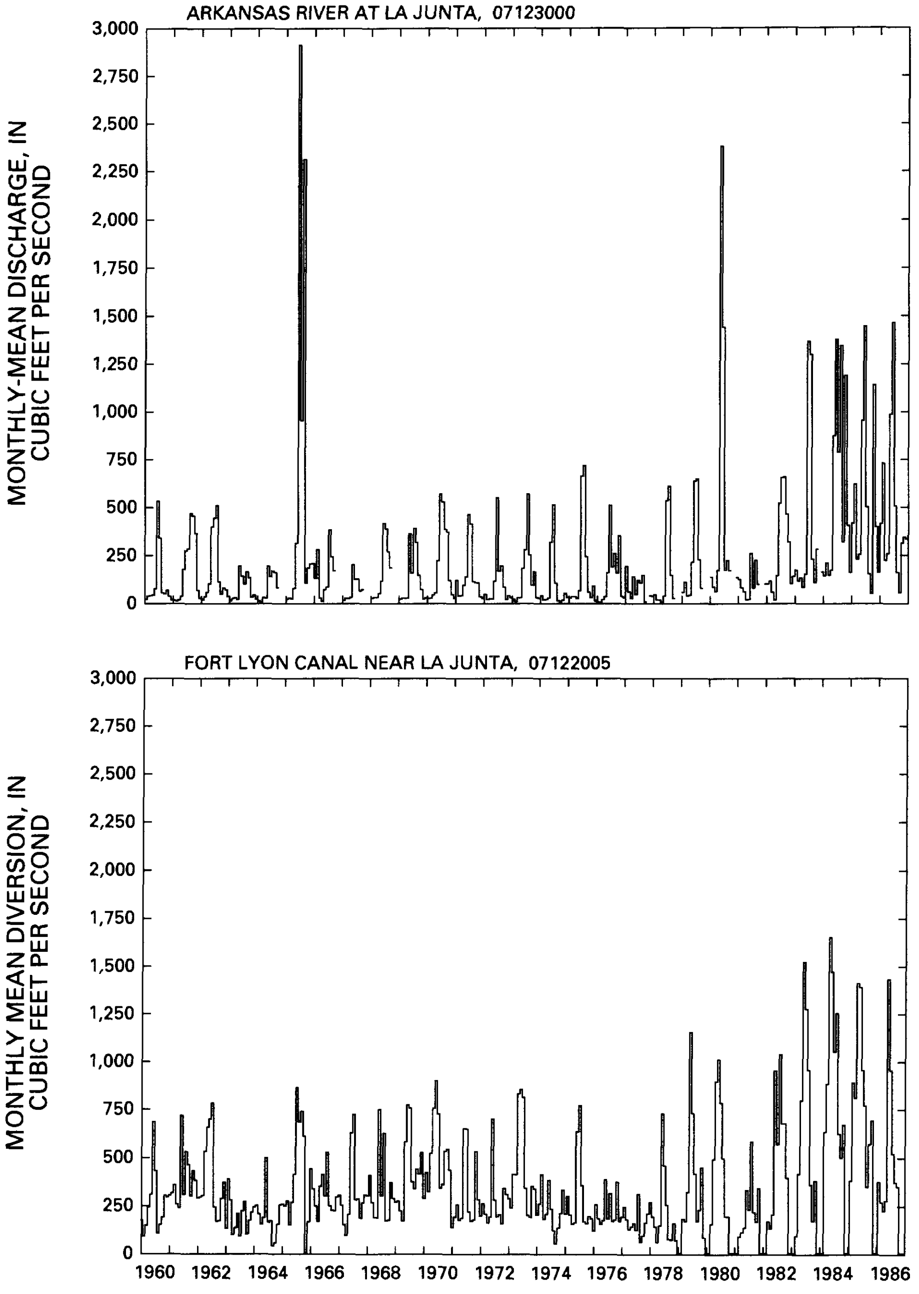

Figure 6.--Monthly mean discharge of the Arkansas River at La Junta (station 07123000) and monthly mean diversions by the Fort Lyon Canal near La Junta (station 07122005), 1960-86.

The altitude of the riverbed at gaging station 07123000 has fluctuated several feet since 1939. The variation in the estimated gage height (height above datum) of the riverbed at the station during 1939-86 is shown in figure 7. The point values shown in figure 7 are gage heights of the point of zero flow defined from stage-discharge ratings for the gaging station. Stage-discharge ratings were revised more frequently prior to 1967. Since 1967, the shifting-control method (Rantz and others, 1982, p. 385-387) has been used, rather than redefining the stage-discharge rating. Therefore, the values after 1967 only indicate long-term trends in the gage height of the bed of the Arkansas River at the gaging station. Data prior to 1961 were compiled by C.T. Jenkins (U.S. Geological Survey, written commun., 1961); data after 1961 were estimated from rating tables in the files of the U.S. Geological Survey. The gage height of the riverbed is estimated to have increased about 2 ft during 1960-86.

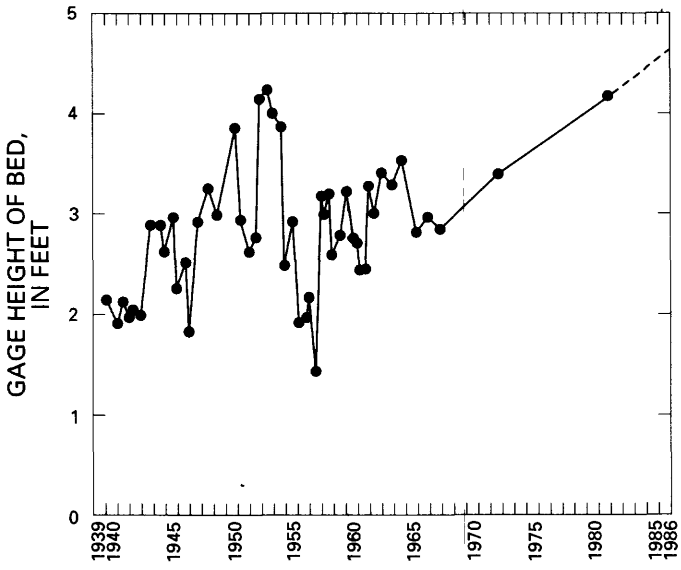

Figure 7.--Estimated gage height of the bed of the Arkansas River at La Junta (station 07123000), 1939-86. Solid line indicates trends between data points. Dashed line is extrapolated trend. Lines do not infer intermediate values. Datum of gage is 4,039.6 feet above NGVD of 1929.

Gain-loss investigations on a 15-mi reach of the river below the Fort Lyon Canal diversion dam (Moore and Wood, 1967) determined net losses of 7 ft^3/s on May 15, 1964 (prior to the ground-water irrigation season) and 37 ft^3/s on July 17, 1964 (during the ground-water irrigation season) indicating that stream-aquifer interaction varies temporally. Average loss ranged from about 0.5 to 2.5 (ft^3/s)/mi. Moore and Jenkins (1966) reported a probable maximum infiltration rate (Q/A; where, Q = infiltration and A = area of streambed) of about 2 ft/d when the river was less than 100 ft wide, its average depth was about 0.7 ft, and pumping of nearby irrigation and municipal wells probably had lowered the water table to levels below the riverbed.

Assuming that the hydraulic connection between the river and the aquifer was broken, then the infiltration rate (Q/A) is a maximum rate which is proportionate to the depth (Δh) of water in the river and is independent of the head difference between the river stage and water table. Because of possible measurement errors, the maximum infiltration rate of 2 ft/d (Moore and Jenkins, 1966) may be in error by 50 percent, and the maximum infiltration rate may range from 1 to 3 ft/d. The discharge rates at the upstream and downstream ends of the 1-mi-long reach, for which Moore and Jenkins (1966) estimated the maximum infiltration rate of 2 ft/d, were 66.4 and 54.2 ft^3/s. Assuming a possible error of 5 percent in the discharge measurements, then the discharge rates could have been 63.1 to 69.7 ft^3/s at the upstream site and 51.5 to 56.9 ft^3/s at the downstream site. The minimum loss would have been 6.2 ft^3/s and the maximum loss 18.2 ft^3/s, for an average of 12.2 ft^3/s. The error in estimated infiltration rate is plus or minus 6 ft^3/s or about 50 percent of the estimated loss of 12.2 ft^3/s. The ratio of infiltration (Q) to water depth (Δh) equals the streambed conductance (KA/L, K = hydraulic conductivity of the streambed, A = area of streambed, and L = streambed thickness). For a hypothetical stream reach with a width of 100 ft and a length of 660 ft (A = 66,000 ft^2), the conductance of the streambed would range from about 94,000 to 282,000 ft^2/d. The streambed leakance (K/L) would range from about 1.4 to 4.3 d^{-1}, and average of about 2.9 d^{-1}. If the hydraulic connection between the river and aquifer were not broken, then the estimated value of streambed leakance would be greater, because the hydraulic gradient would be much less than 0.7/L.

Estimated Ground-Water Budget

A ground-water budget is the summation of the recharge, discharge, and storage changes for the aquifer during a given period of time. Because direct measurement of the rates of recharge and discharge generally are not available, the errors in the budget estimates can be large. Selection of a time period during which water-level change is relatively small eliminates the need to estimate the storage changes.

Estimated annual rates of recharge and discharge of the aquifer during 1960-79 are listed in table 1. (All values in table 1 and the associated text are rounded to the nearest 5 acre-ft.) Although water levels during 1960-79 (fig. 4) fluctuated in response to seasonal and annual variations in rates of recharge and discharge, generally no long-term storage changes are indicated for 1960-79.

The ground-water budget is based on previously published estimates, except that the net rate of flow between the aquifer and river was estimated as the difference between the other budget components. Therefore, the estimate of net surface-water leakage (gain minus loss) also contains the net errors in estimates of the other budget components. (Sources of data and the description of the estimation methods are provided later in the report.)

Table 1.--*Estimated average annual ground-water budget, 1960-79*

[All values rounded to the nearest 5 acre-feet]

Budget component	Annual volume (acre-feet)
Recharge:	
Leakage from Arkansas River[1]	5,710
Leakage from Fort Lyon Canal	3,910
Deep percolation, irrigated land	3,045
Deep percolation, non-irrigated land	140
Underflow	1,320
Total recharge	14,125
Discharge:	
Leakage to Arkansas River[1]	0
Pumpage, municipal	2,800
Pumpage, irrigation and industrial	7,055
Evapotranspiration	2,940
Underflow	1,330
Total discharge	14,125
Storage-Change	0

[1]Leakage was calculated as the difference between the sum of other estimated recharge components (3,910 + 3,045 + 140 + 1,320 = 8,415) and the sum of the estimated discharge components (2,800 + 7,055 + 2,940 + 1,330 = 14,125) and, therefore, is the sum of net leakage, the difference between gains and losses from the river, and errors in other estimates of recharge and discharge.

The hydrologic factors that affect ground-water flow and storage in the study area are: Ground-water surface-water interaction; leakage from the Fort Lyon Canal; deep percolation of precipitation and irrigation water; pumpage for municipal, irrigation, and industrial supply; evapotranspiration; underflow; and storage changes. Aggradation of the bed of the Arkansas River also affects the local hydraulic gradient and, consequently, leakage from or to the river by raising the river stage for a given river discharge; the causes of aggradation were not investigated during this study. Man's use of water in the study area affects recharge and discharge from the aquifer. Only deep percolation of precipitation on non-irrigated land, underflow, and potential evapotranspiration rates are not strongly affected by water-use practices in the study area.

The net leakage from a 6.75-mi reach of the river to the aquifer was estimated as the difference between the sum of the other recharge components and the sum of the discharge components. The estimated rate of leakage from the river was 5,710 acre-ft/yr, which is approximately 1.2 $(ft^3/s)/mi$ of river reach. This value is consistent with the net losses of 0.5 and 2.5 $(ft^3/s)/mi$ measured in 1964 (Moore and Jenkins, 1966).

Leakage from the Fort Lyon Canal averages about 1 $(ft^3/s)/mi$ (C.T. Jenkins, U.S. Geological Survey, written commun., 1961). Estimated leakage loss from the 5.4-mi reach of the canal in the study area is about 3,910 acre-ft/yr [1 $(ft^3/s)/mi \cdot 5.4\ mi \cdot 86,400\ s/d \cdot 365.25\ d/yr\ /\ 43,560\ ft^2/acre$ = 3,910 acre-ft/yr]. (Note, it was assumed that the canal contained water throughout the period.)

Weist (1965) estimated that 25 percent of applied irrigation water percolates to the water table; Konikow and Bredehoeft (1973) estimated the rate at 32 percent. The average rate of percolation of applied irrigation water is assumed to be about 29 percent of total application. Total application, which includes surface-water diversions, ground-water pumpage, and precipitation, is estimated at about 5 ft/yr (Taylor and Luckey, 1972, p. 26). Estimated irrigated acreage in the study area is about 2,100 acres (Konikow and Bredehoeft, 1973, fig. 15). Estimated recharge of deep percolation from irrigated land in the study area is about 3,045 acre-ft/yr (2,100 acres $\cdot$ 5 ft/yr $\cdot$ 0.29 = 3,045 acre-ft/yr). Weist (1965, p. 17) states,

> "The average annual recharge to the irrigated lands along the valley from precipitation was assumed to be 0.2 foot per year. This amount of recharge is greater than for areas of dryland farming because the zone of aeration is kept moist by constant applications of water."

Deep percolation of precipitation on nonirrigated land has not been determined in the study area but was assumed to be about 5 percent of annual precipitation (11 in.) or about 0.05 ft/yr. Recharge from deep percolation of precipitation on nonirrigated land in the study area is estimated at about 140 acre-ft/yr (2,774 acres $\cdot$ 0.05 ft/yr = 139 acre-ft/yr).

The rate of underflow into the study area, calculated using Darcy's Law, was about 1,320 acre-ft/yr. Darcy's Law states that the flow (Q) through a cross-sectional area (A) of saturated aquifer is proportional to the hydraulic conductivity (K) and the hydraulic gradient I, $Q = -KIA \cos\alpha$. The angle α is the angle between the cross section and a cross section oriented normal to the hydraulic gradient. At the western boundary of the study area, assuming that $K = 670$ ft/d, $I = -1.61\times10^{-3}$, $A = 178,445\ ft^2$, and $\alpha = 35°$ $\{-[670\ ft/d \cdot (-1.61 \times 10^{-3}) \cdot 178,445\ ft^2 \cdot \cos 35° \cdot 365.25\ d/yr\ /\ 43,560\ ft^2/acre]$ = 1,320 acre-ft/yr$\}$. Flux from the alluvial aquifer in tributaries along the southern boundaries was assumed to be relatively insignificant and was not included in the budget.

Municipal pumpage by La Junta was about 2,800 acre-ft/yr during the early 1960's (Weist, 1965). Irrigation pumpage in the Arkansas River valley was estimated at about 139 acre-ft per well during 1960 (Weist, 1965, p. 46) and about 196 acre-ft per well during 1971 (Konikow and Bredehoeft, 1973, fig. 21). Assuming an average rate of about 168 acre-ft/yr per well for the 41 irrigation wells and 1 industrial well in the study area, combined irrigation and industrial pumpage is about 7,056 acre-ft/yr (42 wells $\cdot$ 168 acre-ft per well per year = 7,056 acre-ft/yr).

Evapotranspiration of ground water occurs in areas where the water table is near land surface or is in the root zone of phreatophytes. Evapotranspiration is the combination of the processes of evaporation from soil and water surfaces and transpiration by plants. The estimated maximum rate of ground-water evapotranspiration in the study area is about 3 ft/yr when the water table is at land surface (Konikow and Bredehoeft, 1973, fig. 10). The extinction depth, depth at which no ground water is evapotranspired, is assumed to be 10 ft (Konikow and Bredehoeft, 1973). Weist (1965) estimated ground-water evapotranspiration rates of about 2.5 ft/yr where the depth to water was less then 5 ft; Weeks and Sorey (1973, table 2) estimated a ground-water evapotranspiration rate at a nearby site of about 1.5 ft where the depth to water was 7 ft. The depth to water ranged from 0 to 10 ft in about 1,960 acres of the study area, as estimated from a comparison of the water-table map (fig. 5) and topographic maps (U.S. Army Corps of Engineers, 1977). Assuming an average rate of ground-water evapotranspiration of 1.5 ft/yr at an average depth to water of 5 ft for about 1,960 acres in the study area in which the depth to water was 0 to 10 ft below land surface, discharge by evapotranspiration is estimated at about 2,940 acre-ft/yr (1,960 acres · 1.5 ft/yr = 2,940 acre-ft/yr).

Underflow across the eastern boundary of the study area was estimated using Darcy's Law ($Q = -KIA \cos\alpha$) at a rate of about 1,330 acre-ft/yr. At the eastern boundary of the study area, assuming that K = 670 ft/d, $I = -1.33 \times 10^{-3}$, $A = 205{,}430\ ft^2$, and $\alpha = 30°$ $\{-[670\ ft/d \cdot (-1.33 \times 10^{-3}) \cdot 205{,}430\ ft^2 \cdot \cos 30° \cdot 365.25\ d/yr\ /\ 43{,}560\ ft^2/acre] = 1{,}330\ acre\text{-}ft/yr\}$. Weist (1965, table 6, p. 33) assumed a K of about 800 ft/d, a hydraulic gradient of -1.52×10^{-3}, a cross-sectional area of 211,200 ft^2, and an angle of 30°, to estimate an underflow of about 1,900 acre-ft/yr. The major differences in the estimates are in the hydraulic gradient--a difference equivalent to 1 ft/mi--and in assumed hydraulic conductivity values--a difference of 130 ft/d or about 20 percent of the K assumed in this study. In this study it was assumed that hydraulic conductivity was homogeneous in the study area.

Conceptual Model

The unconfined alluvial aquifer in the Arkansas River valley is considered to be a homogeneous and isotropic aquifer which is bounded below and on its north and south sides by impermeable bedrock. Because the aquifer is thin but highly transmissive, ground-water flow is essentially two-dimensional. The Arkansas River is considered to be a partially penetrating stream that is either a source of recharge to the aquifer when the stage in the river is greater than the altitude of the water table, or a sink for discharge from the aquifer when the gradient is reversed. Net annual flow is from the river to the aquifer at an estimated rate of about 5,710 acre-ft/yr; however, the magnitude and direction of stream-aquifer flux varies seasonally with changes in river stage, water-table altitude, pumpage, and other fluxes.

The Fort Lyon Canal is a head-dependent line source of recharge to the alluvial aquifer. Seepage loss from the canal was estimated at 1 $(ft^3/s)/mi$ or about 3,910 acre-ft/yr in the study area. Surface water diverted from the canal is used to irrigate about 2,100 acres in the study area.

Deep percolation of water from 2,100 acres of irrigated land to the alluvial aquifer is estimated to be about 3,045 acre-ft/yr. Deep percolation of precipitation on 2,775 acres of nonirrigated land is about 140 acre-ft/yr.

Pumpage for the municipal supply of La Junta from three well fields is about 2,800 acre-ft/yr. Pumpage by 41 wells for irrigation and 1 well for industrial supply was estimated to be about 7,055 acre-ft/yr during 1960-79. Pumpage for irrigation varies seasonally and is assumed to be inversely related to the availability of surface water for irrigation.

Evapotranspiration of ground water by phreatophytes and from soil is estimated to be about 3 ft/yr when the water table is at land surface and to be inconsequential when the depth to water is greater than or equal to 10 ft. Evapotranspiration from 1,960 acres in the valley, where the depth to water is less than 10 ft, was estimated to be 2,940 acre-ft/yr. Evapotranspiration varies seasonally and is a complex function of climatic, vegetative, soil, and aquifer conditions.

Estimated underflow across the western boundary and into the study area is about equal to underflow across the eastern boundary and out of the study area. The rates of underflow were about 1,320 and 1,330 acre-ft/yr.

Storage within the alluvial aquifer varies seasonally, as indicated by water-level fluctuations (fig. 4). During 1960-79, water levels within the alluvial aquifer, though seasonally variable, were relatively stable. Changes in the altitude of the streambed (fig. 7), increased flow in the Arkansas River (fig. 6), increased surface-water diversions for irrigation (fig. 6), and an assumed decrease in pumpage for irrigation during the 1980's contributed to an increase in storage (a rise of the water table) within the alluvial aquifer.

SIMULATION OF GROUND-WATER FLOW IN THE ALLUVIAL AQUIFER

A numerical model of ground-water flow in the alluvial aquifer was used to evaluate the potential hydrologic effects of the five proposed water-management alternatives. The model was developed in two stages. Initially, a model of steady-state conditions was developed to test the sensitivity of the system to errors in estimates of the values of hydraulic properties and recharge and discharge conditions. A transient model then was calibrated for monthly conditions that occurred during April 1960-December 1984. The potential hydrologic effects of the five proposed water-management alternatives were evaluated with the calibrated transient model for 1985-86 monthly conditions.

Model Description

The numerical model used in this study--the modular model (McDonald and Harbaugh, 1988)--solves the differential equations for three-dimensional ground-water flow by the finite-difference method. The rectangular grid (fig. 8) contains 23 rows and 40 columns of 660-ft by 660-ft blocks. Properties of the aquifer and recharge and discharge conditions are specified for each of the grid blocks. Because the alluvial aquifer is relatively thin and highly transmissive, vertical flow in the aquifer is assumed to be negligible; therefore, the aquifer was modeled as a single layer, two-dimensional system.

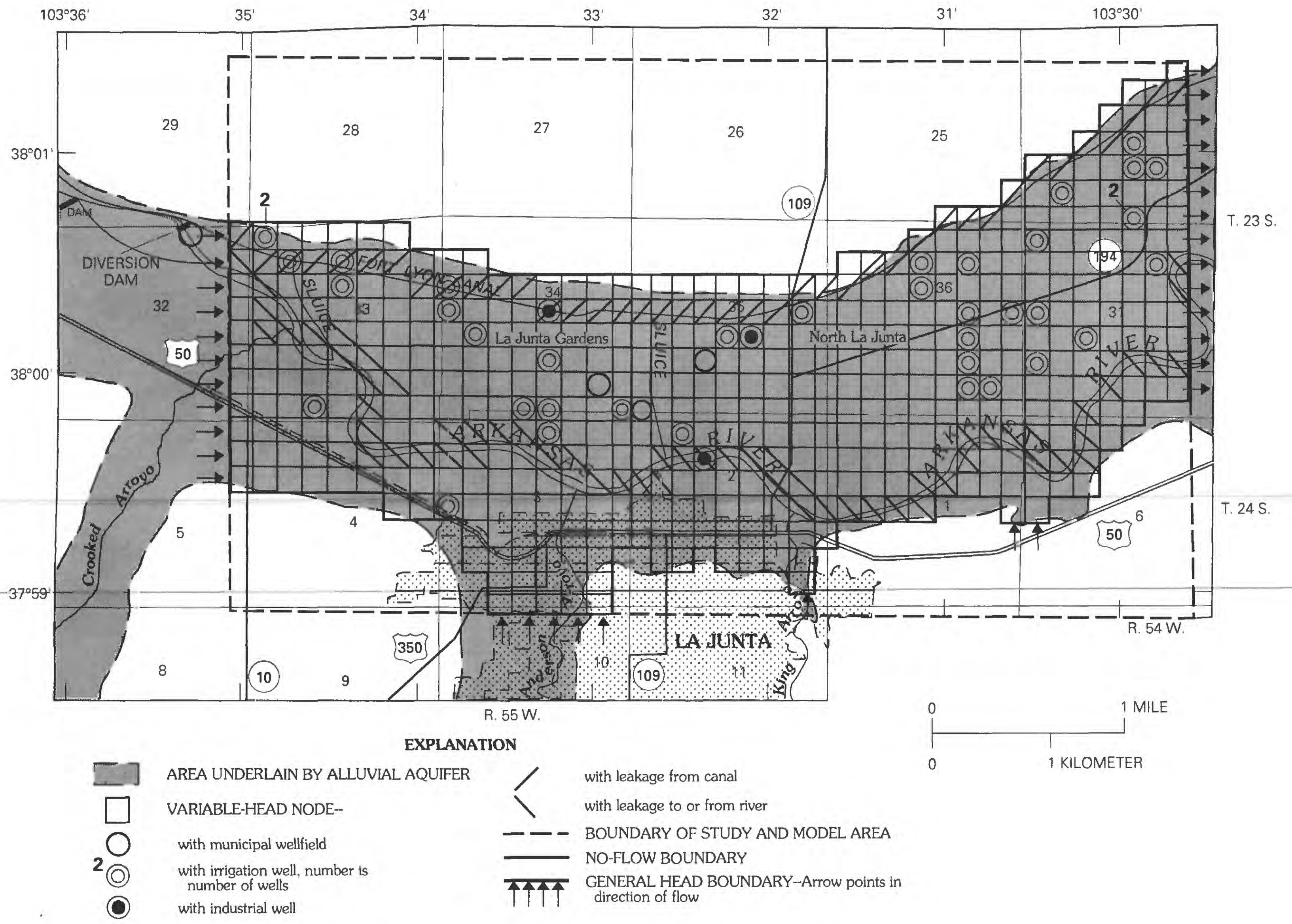

Figure 8.--Model grid, node types, and boundary conditions.

The bedrock at the base of the alluvial aquifer is relatively impermeable shale and limestone; therefore, the bedrock surface (fig. 2) is assumed to be a no-flow boundary. The limits of the saturated alluvial aquifer, on the northern and most of the southern sides of the valley (fig. 8), also are assumed to be no-flow boundaries. Ground-water flow is not considered outside the limits of the saturated alluvial aquifer. Because the alluvial aquifer is continuous outside the modeled area on its eastern and western sides, these artificial model boundaries (fig. 8) are simulated as head-dependent flow boundaries. Ground-water flow into the alluvial aquifer at three small tributary valleys on the southern side of the valley also is modeled with head-dependent flow boundaries.

The heads (water-table altitudes) at the head-dependent flow boundaries were assigned values based on a hydraulic gradient of 7 ft/mi (Nelson and others, 1989). The value of the conductance assigned to the head-dependent flow-boundary nodes was calculated as $C = KWb/L$ where C is the conductance of a hypothetical prism of aquifer outside the boundary, in square feet per day; K is the average hydraulic conductivity of the aquifer in the prism, in feet per day; W is the width of the saturated block face at the boundary, in feet; b is the saturated thickness, in feet; and L is the flow-path length, in feet. For example, assuming a hypothetical value of a hydraulic conductivity of 750 ft/d, a width of 660 ft, a saturated thickness of 20 ft, and a flow-path length of 52,800 ft (10 mi) produces a conductance of 187.5 ft^2/d. Flow (Q) through the boundary is calculated as the product of the conductance (C) and the head difference across the boundary (ΔH), $Q = C\Delta H$. Under steady-state conditions, boundary flow for an assumed 70-ft head difference (7 ft/mi · 10 mi) for the example would be 13,125 ft^3/d. The flow-path length of 52,800 ft (10 mi) was chosen to minimize the effect of the head-dependent flow boundaries during transient simulations.

Because the alluvial aquifer is unconfined, and the water table is near land surface, substantial amounts of water are able to recharge or discharge from the aquifer in a vertical direction at the water table by several processes, which are simulated in the model. These processes include deep percolation from precipitation and excess irrigation water, leakage from the river and canal, and evapotranspiration. Vertical fluxes at the water table are assumed to be instantaneous and flow through the unsaturated zone is not simulated.

Using aquifer properties and hydraulic stresses defined by the modeler, the model calculates head values for the center of each model block, which is called a node. For the purpose of calculating changes in storage of water in the blocks in the transient model, the calculated head is assumed to be uniform over the area represented by the block at any given time.

The hydraulic conductivity of the alluvial aquifer is assumed to be isotropic (the same in all directions) within each block, but was varied between blocks. The values for hydraulic conductivity used in the calibrated model were either 750 or 1,500 ft/d and are based on a map of the transmissivity of the aquifer (Konikow and Bredehoeft, 1973, fig. 5) and a map of the saturated thickness in spring 1966 (fig. 3). Specific yield for transient simulations was assumed to be a uniform value of 0.20.

The calibrated value for the conductance of the bed of the Arkansas River was 21,600 ft^2/d. Assuming a reach length of 660 ft and reach width of 100 ft, the leakance (K/L) of the riverbed was simulated at 0.33 d^{-1}, which is about one-tenth of the leakance of 2.9 d^{-1} estimated from infiltration rates reported by Moore and Jenkins (1966). At a stage of 1 ft above the riverbed and assuming that the water table was at or below the streambed, leakage (infiltration) would be simulated at a rate of about 2 $(ft^3/s)/mi$, approximately the seepage rate reported by Moore and Jenkins (1966) during the irrigation season.

The calibrated value for conductance of the bed of the Fort Lyon Canal was 9,000 ft^2/d. Assuming a reach length of 660 ft and a reach width of 60 ft, the leakance of the canal bed was simulated at 0.23 d^{-1}. At a stage of 1.46 ft (the estimated average stage in the canal during 1960-79) and assuming that the water table was always at or below the canal bed, steady leakage would be simulated at a rate of about 1.2 $(ft^3/s)/mi$, slightly larger than the rate reported by C.T. Jenkins (U.S. Geological Survey, written commun., 1961).

The Steady-State Model, 1960-79 Conditions

A numerical model of the alluvial aquifer was calibrated for average 1960-79 (steady-state) conditions when recharge was assumed to approximately equal discharge and when there was no long-term storage change. The steady-state model was used to evaluate the sensitivity (system response) to changes in values of the estimated hydraulic properties of the aquifer, riverbed and canal bed, and of selected recharge and discharge conditions. Although a true steady-state condition did not exist for the stream-aquifer system during 1960-79, long-term hydrographs (figs. 4 and 6) indicate that water levels, streamflow, and canal diversions fluctuated seasonally, but were in approximate equilibrium from year to year. Franke and others (1987, p. 11) state, "If a certain pattern of stress on the ground-water system remains unchanged for a sufficiently long period, the system may achieve equilibrium with stress." Therefore, a reasonable approximation of steady-state conditions can be assumed for 1960-79 conditions in the study area.

Pumpage for municipal supply was simulated at three nodes (fig. 8) at a combined rate of 2,761 acre-ft/yr (2.5 million gal/d). The difference between the simulated rate and the estimated rate of 2,800 acre-ft/yr (table 1), is a rounding error. Pumpage by 41 irrigation wells and by 1 industrial well was simulated at 39 nodes (fig. 8), at 167.5 acre-ft/yr per well or a combined rate of about 7,035 acre-ft/yr. Areal recharge (deep percolation) was simulated at a rate of about 1.3 ft/yr on irrigated land and at a rate of about 0.05 ft/yr on nonirrigated land. The distribution of areal recharge that is used in the steady-state model is shown in figure 9.

Ground-water surface-water interaction and evapotranspiration are simulated as head-dependent functions in the model. The Arkansas River and Fort Lyon Canal were simulated by using the river option of the model (McDonald and Harbaugh, 1988). Data specified for each river node (fig. 8) were the altitudes of the bed and water surface of the river or canal and the conductance of the bed for each river node. Bed altitudes for nodes simulating the Arkansas River and Fort Lyon Canal were estimated from topographic maps with a 2-ft contour interval (U.S. Army Corps of Engineers, 1977), for most of the

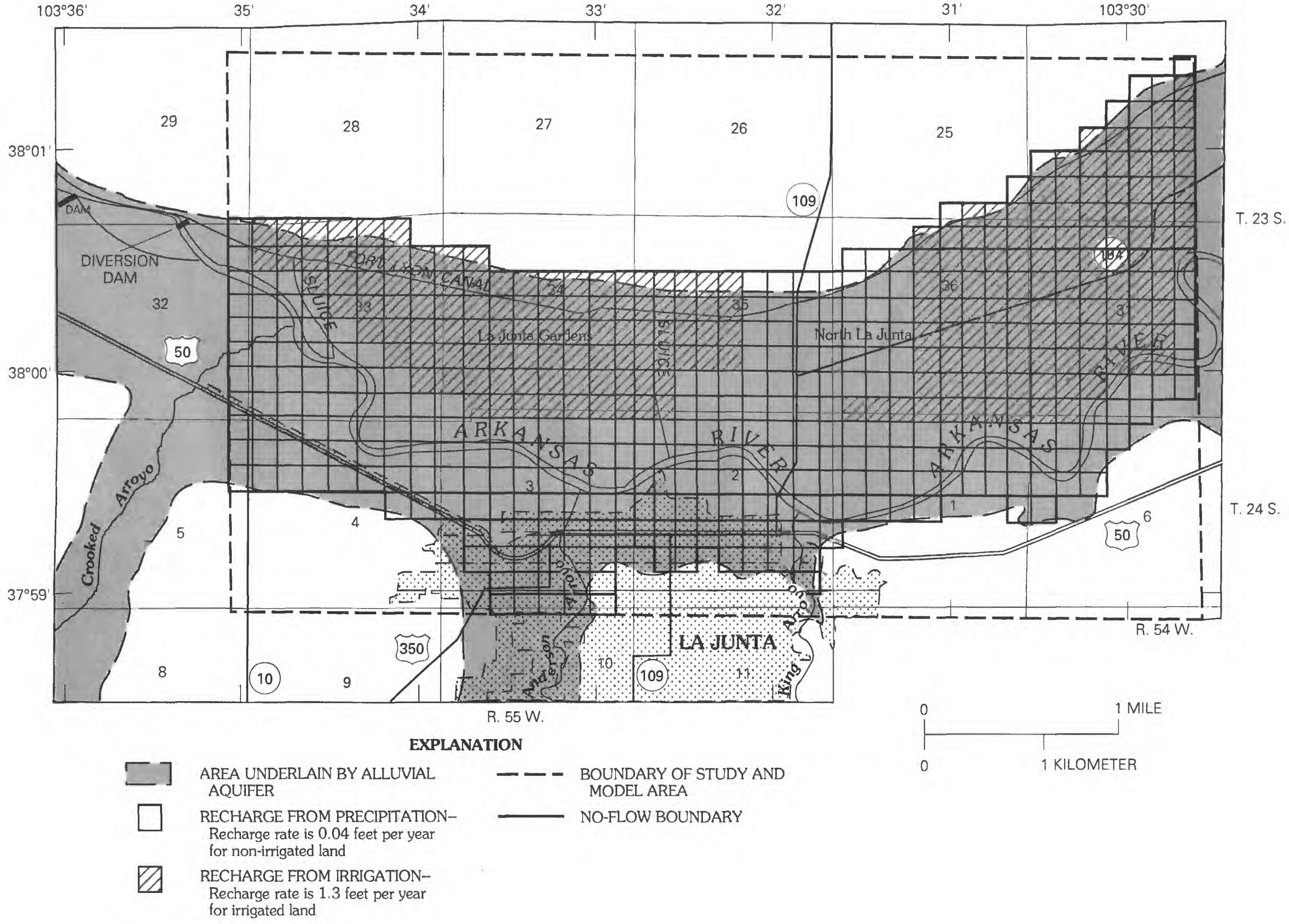

Figure 9.--Simulated steady-state recharge rates.

area, and from 7½-minute topographic quadrangles with a 10-ft contour interval for the remaining areas. The altitudes of the riverbed nodes were adjusted, based on the estimated change in the altitude (fig. 7) of the riverbed between the date of the topographic control (1977) and 1970 (the middle year of the steady-state period). The average stage for the Arkansas River at La Junta was estimated to be 0.95 ft above the riverbed and for the Fort Lyon Canal near La Junta to be 1.46 ft in the flume from discharge rating tables and the 1960-79 mean discharge of the river or diversion rate of the canal. The stage at each river node was assigned either a value of 0.95 ft above the estimated altitude of the riverbed or a value of 1.46 ft above the estimated altitude of the canal bed because it was assumed that the channel geometries of the river and canal were relatively uniform in the modeled area.

The rate of ground-water evapotranspiration was assumed to be 3 ft/yr when the water table was at land surface and to be zero when the depth to water was 10 ft or more (fig. 10). The depth to water at which ground-water evapotranspiration is assumed to be zero is referred to as the extinction depth. The altitude of the land surface for most of the area was interpolated from the topographic maps that have a 2-ft contour interval (U.S. Army Corps of Engineers, 1977) and from 7½-minute topographic quadrangles that have a 10-ft contour interval in the remaining area.

Calibration of the Steady-State Model

During calibration of the steady-state model, selected simulated hydraulic characteristics of the aquifer, riverbed, and canal bed, and areal recharge rates were varied to obtain a better fit between simulated heads and historic water levels and between simulated and estimated losses of the river and canal.

Values of hydraulic conductivity, which initially were specified in multiples of 670 ft/d and which ranged from 670 to 2,010 ft/d (Konikow and Bredehoeft, 1973, fig. 5), were modified to either 750 or 1,500 ft/d. The conductance of the bed of the Arkansas River was reduced from an initial value of 132,000 ft^2/d (equivalent to an infiltration loss of about 12 $(ft^3/s)/mi$ at a stage of 0.95 ft) to 21,600 ft^2/d (a loss of about 2 $(ft^3/s)/mi$), because simulated net leakage from the river, using the initial values, was much larger than previously estimated, and the simulated heads were larger than historic water-table altitudes. The simulated conductance of the bed of the Fort Lyon Canal was reduced from 14,400 ft^2/d to 9,000 ft^2/d, so simulated heads would approximate 1960-79 water-table altitudes in wells near the canal. Areal recharge from irrigated lands was reduced from 1.45 ft/yr to 1.3 ft/yr or from 29 to 26 percent of the assumed application rate of 5 ft/yr.

Model Sensitivity

Sensitivity tests of the steady-state model were performed by changing the values of simulated hydraulic properties and recharge or discharge conditions within a limited range to evaluate the effects of possible errors in the specified values. The sensitivity of the model to the change in a simulated hydraulic property or recharge or discharge condition can be judged by the effects on the simulated ground-water budgets and on simulated heads. The components of the estimated ground-water budget from table 1 also are listed

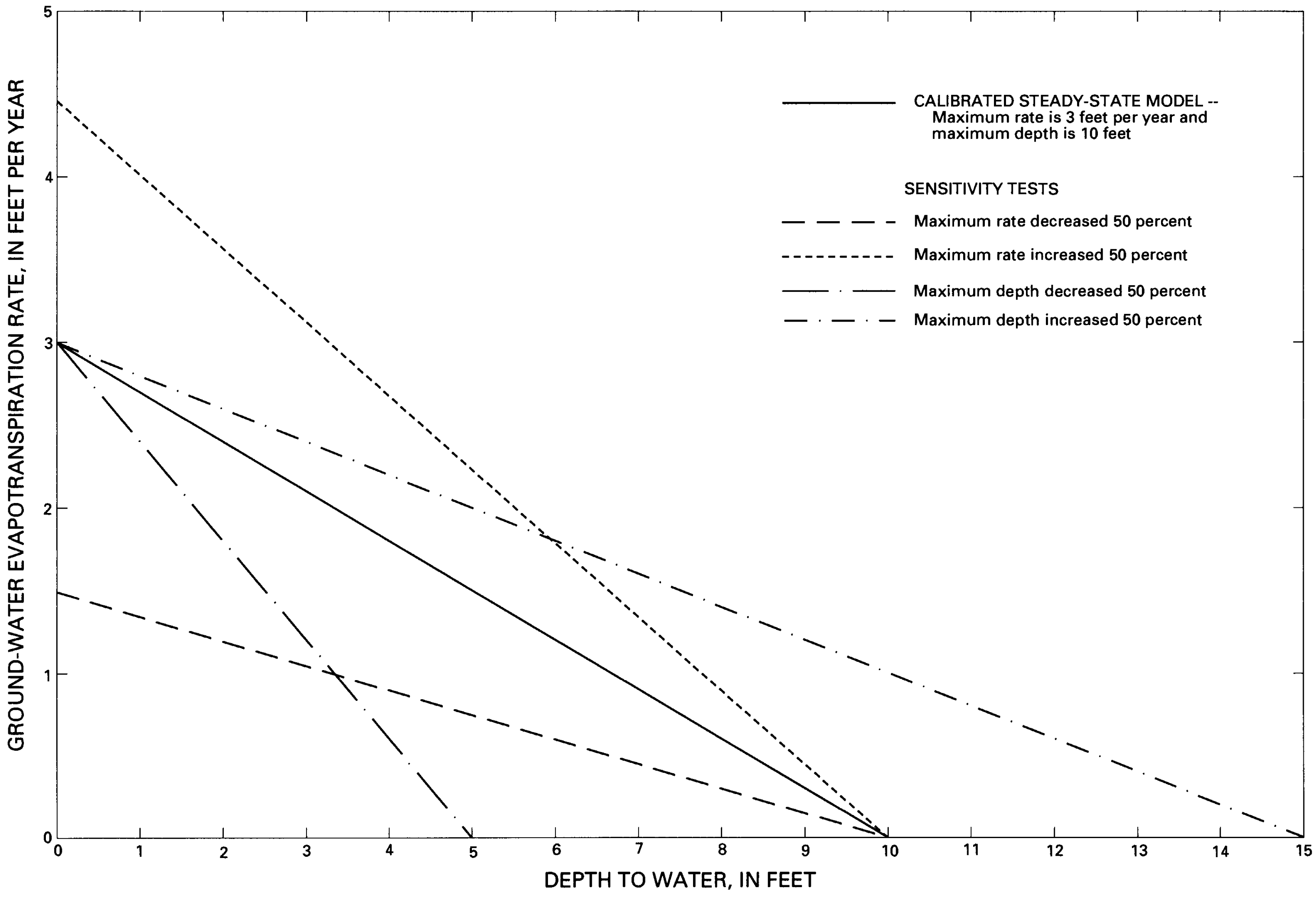

Figure 10.--Relation of ground-water evapotranspiration to depth to water.

in table 2 for comparison with simulated budget components. The head change for each active node was calculated as the difference between simulated head for the sensitivity test minus simulated head for the calibrated model. Results from the sensitivity tests can be used to evaluate the range of possible errors in simulated budgets and heads from the steady-state model, assuming that the hydraulic property or recharge or discharge condition is misspecified in the calibrated model.

Results from the sensitivity tests of the calibrated steady-state model indicate that simulated heads are sensitive to the simulated altitude of the stage and bed of the river. Decreasing simulated river stage and bed altitudes by 4 ft caused a median head difference (decline) of -3.3 ft; conversely, increasing the simulated river stage and bed altitudes by 4 ft caused a median head difference (rise) of 3.1 ft from simulated heads for the calibrated steady-state model (table 2). Simulated steady-state heads also were sensitive to simulated pumpage rates and the simulated conductance of the beds of the river and canal.

In general, errors in specification of most of the hydraulic properties and recharge or discharge conditions would result in errors in simulated rates of leakage to and from the river and evapotranspiration, both of which are head-dependent fluxes. The agreement between the estimated steady-state budget and the simulated steady-state budget for the calibrated model (table 2) is relatively good. However, because many of the specified conditions are poorly defined, the calibrated model represents only one possible solution that could simulate the head distribution in the aquifer.

Simulated net leakage between the aquifer and river, the difference between leakage from and to the river, was from the river to the aquifer for all of the sensitivity tests (table 2). Estimated net leakage for the ground-water budget (table 1) was about 5,710 acre-ft/yr, for the calibrated steady-state model was 5,509 acre-ft/yr, and for the sensitivity tests ranged from 3,034 to 8,392 acre-ft/yr. Simulated net leakage also is sensitive to the estimates of other fluxes.

Rates of simulated evapotranspiration of ground water also were sensitive to the estimates of other fluxes. Estimated discharge by evapotranspiration for the ground-water budget (table 1) was about 2,940 acre-ft/yr, assuming a maximum ground-water evapotranspiration rate of 3 ft and an extinction depth of 10 ft. Discharge by evapotranspiration was simulated at a rate of 3,097 acre-ft/yr in the calibrated steady-state model and ranged from 875 to 5,876 acre-ft/yr for the sensitivity tests.

Because leakage between the aquifer and river and evapotranspiration were the only source-sink terms, other than underflow, whose simulated rates were functions of heads in the aquifer, errors in estimating the conductance, and altitudes of the river stage and bed and in the maximum evapotranspiration rate and extinction depth mask the errors in estimating the specified steady fluxes, such as pumpage, deep percolation, and leakage from the Fort Lyon Canal. The set of hydraulic characteristics and recharge and discharge conditions chosen for the steady-state model produced a good fit between simulated heads and historic water levels while still approximating the estimated ground-water budget. The median change in simulated head for the calibrated steady-state model was a rise of 2.2 ft above the April 1960 water-table surface used for the initial condition. This difference is within the range of historic seasonal fluctuations of water levels (fig. 4).

Table 2.--*Estimated ground-water budget for 1960-79 and simulated steady-state ground-water budgets and head differences for the calibrated model and sensitivity tests*

[All budget values are rounded to the nearest acre-foot per year. Estimated budget values are from table 1. NA, not applicable]

Hydraulic roperty or echarge or discharge condition changed	Change from calibrated model (percent)	Ground-water budget: Recharge: Deep percolation	Recharge: Leakage, Fort Lyon Canal	Recharge: Leakage, Arkansas River	Recharge: Underflow	Discharge: Total pumpage[1]	Discharge: Evapotranspiration	Discharge: Leakage, Arkansas River	Discharge: Underflow	Budget discrepancy (recharge minus discharge)	Median head difference[2] (feet)
						Estimated					
None	NA	3,185	3,910	[3]5,710	1,320	9,855	2,940	[3]0	1,330	0	NA
						Calibrated model					
None	NA	2,826	4,407	6,029	1,516	9,796	3,097	520	1,358	7	--
						Sensitivity tests					
Hydraulic conductivity	-50	2,826	4,407	5,424	1,485	9,796	2,876	187	1,272	11	-0.4
Hydraulic conductivity	+50	2,826	4,407	6,523	1,543	9,796	3,196	921	1,385	1	.1
Conductance of canal bed	-50	2,826	2,204	7,342	1,526	9,796	2,616	159	1,319	8	-.9
Conductance of canal bed	+50	2,826	6,611	4,712	1,509	9,796	3,571	895	1,388	8	.7
Conductance of river bed	-50	2,826	4,407	4,638	1,539	9,796	2,122	140	1,350	2	-1.3
Conductance of river bed	+50	2,826	4,407	6,544	1,509	9,796	3,334	791	1,358	7	.3
Altitude of river bed	[4]-4	2,826	4,407	3,923	1,514	[5]9,629	875	889	1,264	13	-3.3
Altitude of river stage and bed	[4]+4	2,826	4,407	8,637	1,467	9,796	5,876	245	1,414	6	3.1
Maximum evapotranspiration rate	-50	2,826	4,407	4,855	1,513	9,796	1,673	762	1,363	7	.3
Maximum evapotranspiration rate	+50	2,826	4,407	7,018	1,520	9,796	4,280	338	1,353	4	-.3
Maximum evapotranspiration depth	-50	2,826	4,407	4,282	1,511	9,796	933	923	1,366	8	0.5
Maximum evapotranspiration depth	+50	2,826	4,407	7,512	1,524	9,796	4,902	219	1,344	8	-.6
Deep percolation rate	-50	1,413	4,407	6,854	1,520	9,796	2,812	239	1,337	10	-.5
Deep percolation rate	+50	4,239	4,407	5,199	1,514	9,796	3,383	797	1,376	7	.4
Pumpage, irrigation and industrial	-50	2,826	4,407	4,054	1,506	6,278	3,812	1,296	1,397	10	.8
Pumpage, irrigation and industrial	+50	[5]2,825	4,407	8,234	1,530	13,313	2,371	29	1,277	6	-1.4
Pumpage, municipal	-50	2,826	4,407	5,047	1,516	8,416	3,385	627	1,360	8	.4
Pumpage municipal	+50	2,826	4,407	6,960	1,518	11,177	2,743	429	1,354	8	-.5

[1]Total pumpage is the sum of municipal pumpage (2,761 acre-feet per year) and irrigation-industrial pumpage (7,035 acre-feet per year).

[2]Median head difference is the median value of the differences between simulated heads for the sensitivity tests and the calibrated model for each active node. Negative values indicate a decline in head, positive values a rise.

[3]Leakage in the estimated budget is the net (recharge minus discharge) leakage.

[4]Changes in altitudes of the river stage and bed are in feet.

[5]One or more nodes went dry during the simulation, affecting the simulated budget values.

Errors in the steady-state model primarily result from errors in the estimates of the factors (altitudes of surfaces and rates) controlling head-dependent flow, the specified recharge and discharge rates, and in hydraulic conductivity. The values of hydraulic conductivity of the aquifer and the reported rates of municipal pumpage are relatively well defined and probably are not major sources of model error. The conductance of the bed of the Arkansas River and of the Fort Lyon Canal, the ground-water evapotranspiration rate and extinction depth, the areal recharge rates, and the irrigation and industrial pumpage are not well defined and could be sources of error in the steady-state model. Because evapotranspiration and leakage from the river and canal are head-dependent functions and are major fluxes of the system, errors in estimating the altitudes of the land surface and the river and canal stages and beds can substantially affect the reliability of the model results.

The Transient Model, April 1960-December 1984 Conditions

The model of 1960-79 steady-state conditions was modified to simulate monthly April 1960-December 1984 transient conditions. The rise in the water levels after 1979 (fig. 4) indicates that recharge-discharge conditions and (or) boundary conditions (such as a rise in river stage) changed. Increases in the stages in the Arkansas River and in the Fort Lyon Canal affected recharge-discharge conditions.

The transient period, April 1960-December 1984, was simulated with 297 stress periods, each of which simulated a month, and within which the specified flow rates and heads at the head-dependent flow nodes were constant. Areal recharge rates were held constant for the entire transient period at 1.3 ft/yr for the irrigated areas and at 0.05 ft/yr for nonirrigated areas (fig. 9). The heads and conductance values at the head-dependent flow boundaries were held constant for the entire transient period.

The altitudes of the water surface (stage) and bed of the Arkansas River were varied during the transient period. Changes in stage above the riverbed were estimated from the monthly mean discharge of the Arkansas River at La Junta (fig. 6) and stage-discharge ratings for station 07123000. Temporal changes in the altitude of the riverbed were estimated from figure 7. Simulated stage of the water surface and altitude of the bed of the Arkansas River for the node representing the 10-acre parcel in which station 07123000 is located are shown in figure 11. The datum for station 07123000 is 4,039.6 ft above sea level. During 1976, the estimated gage height of the riverbed was 3.7 ft above datum; altitude of the riverbed was about 4,043.3 ft above sea level. The simulated altitude of the riverbed at the center of the cell nearest the gaging station was 4,044.5 ft. The discrepancy in altitudes is the result of a slight difference in the locations of the gage and the node. Because the Arkansas River is a sand-channel stream in this reach, the altitude of the streambed can vary over short intervals, depending on sediment load and flow conditions. The simulated altitude of the riverbed shown in figure 11 only indicates the general trend in change in the altitude of the riverbed. Uniform corrections to the altitudes of the riverbed and estimated stages resulting from aggradation were assumed for the 62 river nodes in the model. Conductance of the riverbed was not modified for the increased streambed thickness that would be associated with aggradation of the riverbed. An increase in streambed thickness also would be accompanied by an increase in river stage, which would partially compensate for a reduction in conductance.

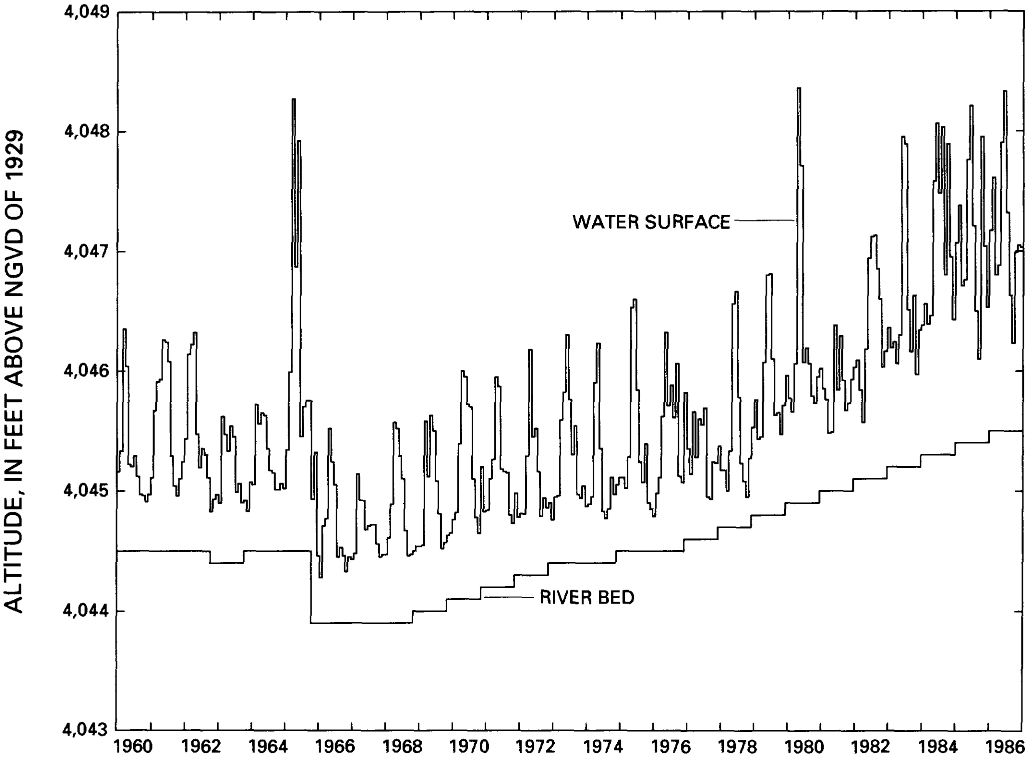

Figure 11.--Simulated altitudes of the water surface and bed of the Arkansas River at La Junta, April 1960-December 1986.

The monthly mean stage of the Fort Lyon Canal, station 07122005, was estimated from monthly mean diversions (discharge) at the flume and a stage-discharge rating table for free-flow conditions in a 40-ft Parshall flume (Kilpatrick, 1965, table 2). Because the flume often is operated under submerged conditions, actual stages in the flume would be higher than estimated. Stages in the canal were not adjusted for variations in the width and gradient of the canal or for diversions from the canal.

The differences between the estimated monthly potential evapotranspiration and the monthly precipitation rates that were estimated by Konikow and Bredehoeft (1973, fig. 10) for March 1971-February 1972 were simulated as the monthly maximum ground-water evapotranspiration rates for the transient period (fig. 12). The sum of the monthly maximum ground-water evapotranspiration rates equals an annual rate of about 3 ft, which was the value used in the steady-state model.

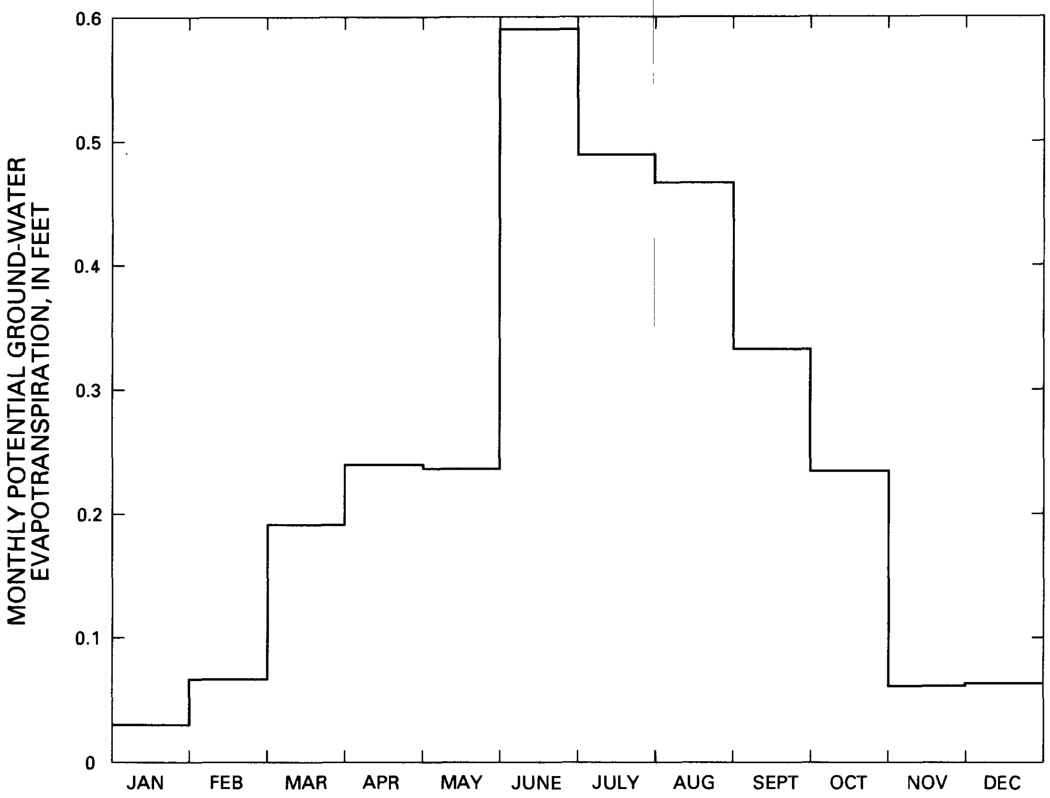

Figure 12.--Simulated monthly ground-water evapotranspiration rates.

Although municipal pumpage by the city of La Junta is metered, records were not available for the entire transient period. Municipal pumpage of about 2,800 acre-ft/yr (Weist, 1965) was assumed for the entire transient period. The distribution of monthly municipal pumpage among the three active well fields (north, south, and west) was based on 1985 daily pumpage data, which were provided by Harold Scofield (Department of Public Works, City of La Junta, written commun., 1987). Pumpage from the east well field, which is no longer used, was not simulated in the transient model.

Because irrigation and industrial pumpage within the study area are not metered, irrigation and industrial pumpage was estimated from reported irrigation withdrawals (Weist, 1965; Konikow and Bredehoeft, 1973) and an assumed inverse relation with surface-water availability. All 41 irrigation wells and the 1 industrial well were assumed to pump at the same rate. Where two irrigation wells were simulated by one node, the simulated pumping rate was doubled. The monthly totals of simulated municipal and irrigation and industrial pumpage are shown in figure 13.

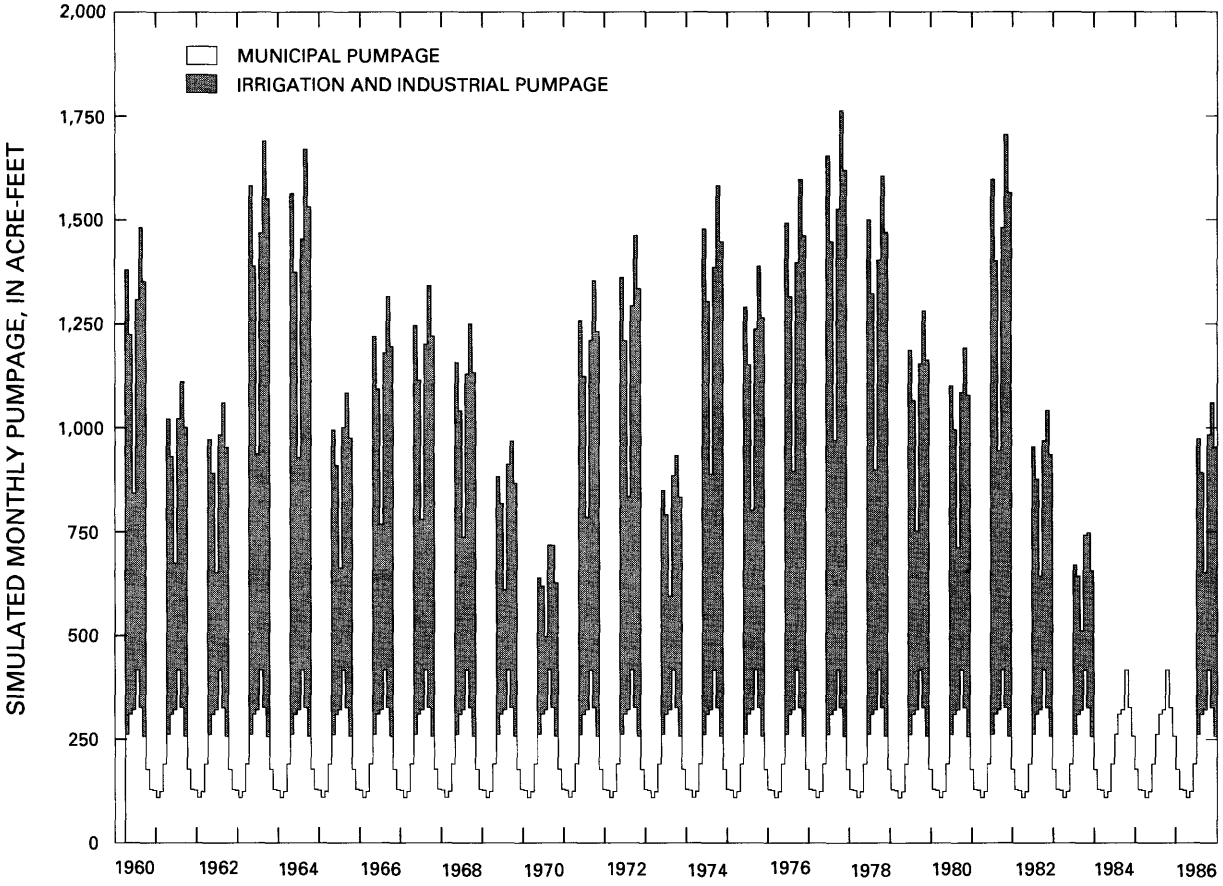

Figure 13.--Simulated monthly pumpage, April 1960-December 1986.

The transient model was calibrated with a specific yield of 0.20. Trial-and-error substitution of selected hydraulic properties of the aquifer, riverbed, and canal bed, and of specified fluxes did not substantially improve the fit of the model. Therefore, the values used in the calibrated steady-state model also were used in the transient model. The model was calibrated to simulate monthly hydrographs of water-table altitudes (fig. 14) in nine long-term observation wells (fig. 1, wells A-I). The hydrographs of simulated heads (fig. 14, wells D, F, H, and I) of wells near the river matched historic water-table altitudes more closely than the hydrographs of simulated heads (fig. 14, wells A, B, and C) for wells in irrigated areas near the canal. This lack of fit in areas near the canal which are irrigated may result from errors in estimating the distribution of irrigation pumpage, canal leakage, and deep percolation. The relatively close fit of simulated heads and water-table altitudes for wells near the river probably result from the dampening effect of this head-dependent flow boundary.

The average annual simulated ground-water budgets for the transient period (April 1960-December 1984) and for two intervals within the transient period (April 1960-December 1979 and January 1980-December 1984) are listed in table 3. The simulated transient-state ground-water budget (table 3) for April 1960-December 1979 approximates the simulated steady-state budget listed in table 2.

Differences between fluxes in the simulated steady-state (table 2) and transient (table 3) budgets for the April 1960-December 1979 period primarily result from differences in estimated pumpage for irrigation and industrial supplies. For the transient simulation, it was assumed that ground-water pumpage for irrigation would occur only if the surface-water supply diverted by the Fort Lyon Canal was insufficient to meet the potential irrigation demand for lands irrigated by the canal. Estimated irrigation-industrial pumpage for the steady-state model was 7,035 acre-ft/yr and for the April 1960-December 1979 transient model averaged about 5,016 acre-ft/yr, a difference of 2,019 acre-ft/yr. (Pumpage for transient conditions was based on availability of surface water diverted by the Fort Lyon Canal.) The difference between the simulated steady-state and transient-state pumpage rates caused an increase of about 183 acre-ft/yr in simulated evapotranspiration and a decrease of about 1,597 acre-ft/yr in simulated net leakage from the river.

Simulated head-dependent flow rates (table 3) changed during January 1980-December 1984, relative to April 1960-December 1979, as a result of a 367-acre-ft/yr increase in net leakage from the Fort Lyon Canal and a 372-acre-ft/yr decrease in net leakage from the river. Leakage from the canal increased because of simulated increased stages in the canal. Net leakage from the river decreased because simulated heads rose, which reduced the simulated hydraulic gradient between the river and aquifer. Net simulated underflow, the difference between underflow into and out of the boundaries, changed from -93 acre-ft/yr during April 1960-December 1979 to -162 acre-ft/yr during January 1980-December 1984. The difference between net underflow for the April 1960-December 1979 and January 1980-December 1984 periods results partially from the artificial nature of the head-dependent flow boundaries (fig. 8). However, the net underflow represents less than 1 percent of the totals of other recharge or discharge components and is not a major source of error in the model. A 1,310-acre-ft/yr increase in simulated ground-water evapotranspiration during January 1980-December 1984 results from the rise in simulated heads.

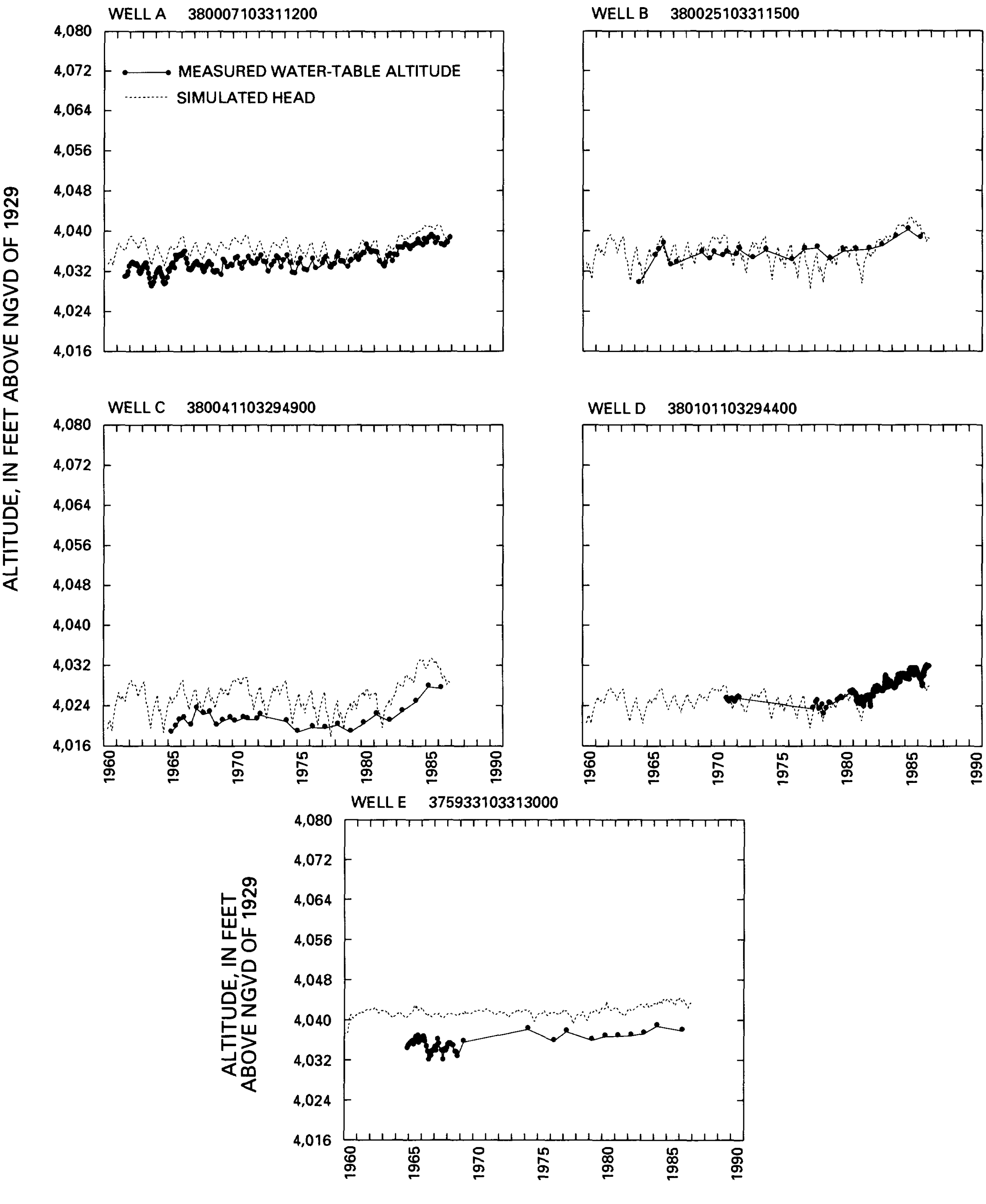

Figure 14.--Simulated monthly heads and measured water-table altitudes, April 1960-December 1984. The 15-digit number following the well designation is the U.S. Geological Survey site-identification number. The lines connecting data points do not infer intermediate values and only are shown to indicate trends.

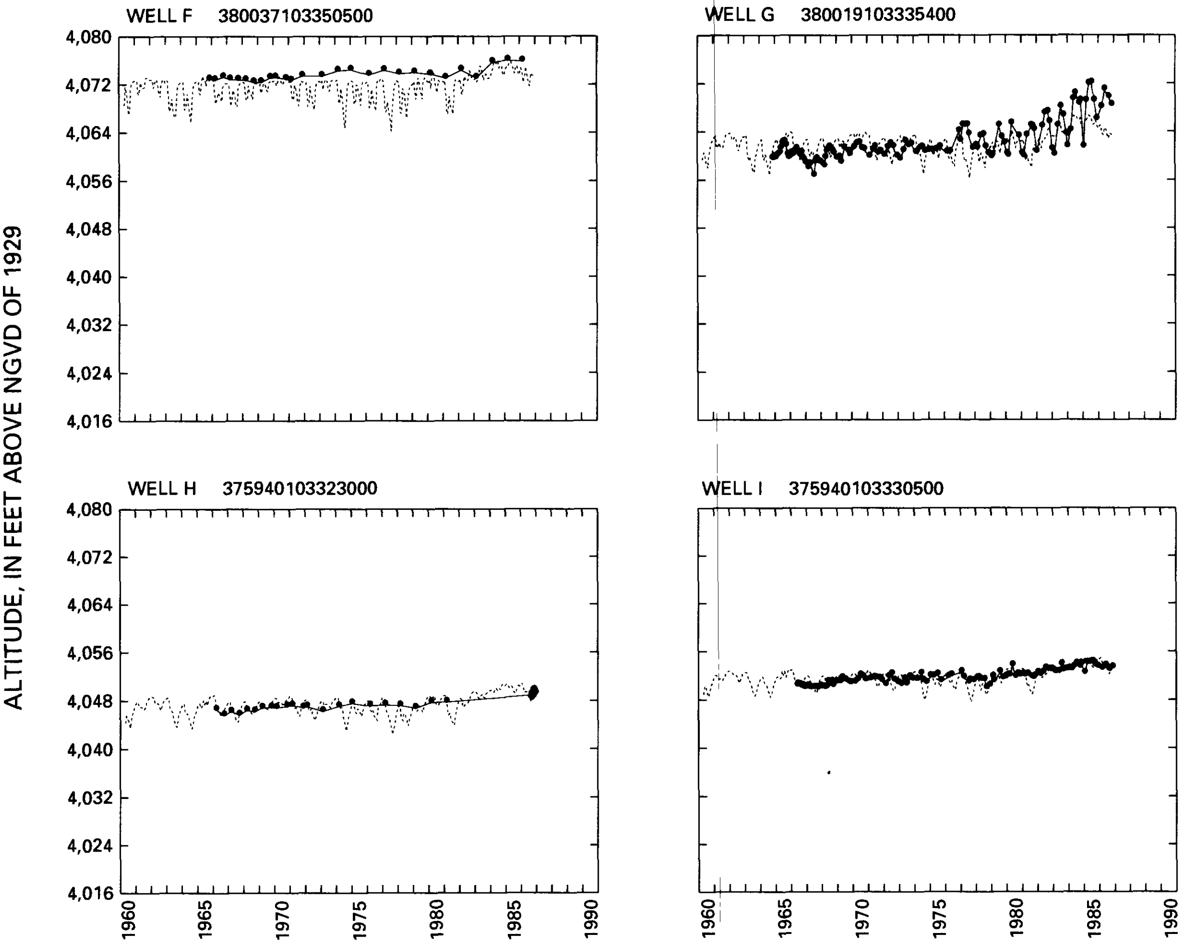

Figure 14.--Simulated monthly heads and measured water-table altitudes, April 1960-December 1984. The 15-digit number following the well designation is the U.S. Geological Survey site-identification number. The lines connecting data points do not infer intermediate values and only are shown to indicate trends--Continued.

Table 3.--*Average annual simulated ground-water budgets for April 1960-December 1984, April 1960-December 1979, and January 1980-December 1984 transient conditions*

[All budget values are rounded to the nearest acre-foot per year]

Transient period	Nominal duration of period (years)	Recharge: Deep percolation	Recharge: Leakage: Fort Lyon Canal	Recharge: Leakage: Arkansas River	Recharge: Underflow	Discharge: Total pumpage	Discharge: Evapotranspiration	Discharge: Leakage to: Fort Lyon Canal	Discharge: Leakage to: Arkansas River	Discharge: Underflow	Storage[1] change	Budget discrepancy (recharge minus discharge minus storage change)
April 1960-December 1984	24.75	2,821	4,553	5,001	1,646	7,423	3,444	16	1,164	1,753	214	7
April 1960-December 1979	19.75	2,824	4,480	5,032	1,652	7,777	3,180	17	1,120	1,745	142	7
January 1980-December 1984	5.0	2,812	4,844	4,877	1,623	6,025	4,490	14	1,337	1,785	498	7

[1]Storage change, positive values indicate increase in storage.

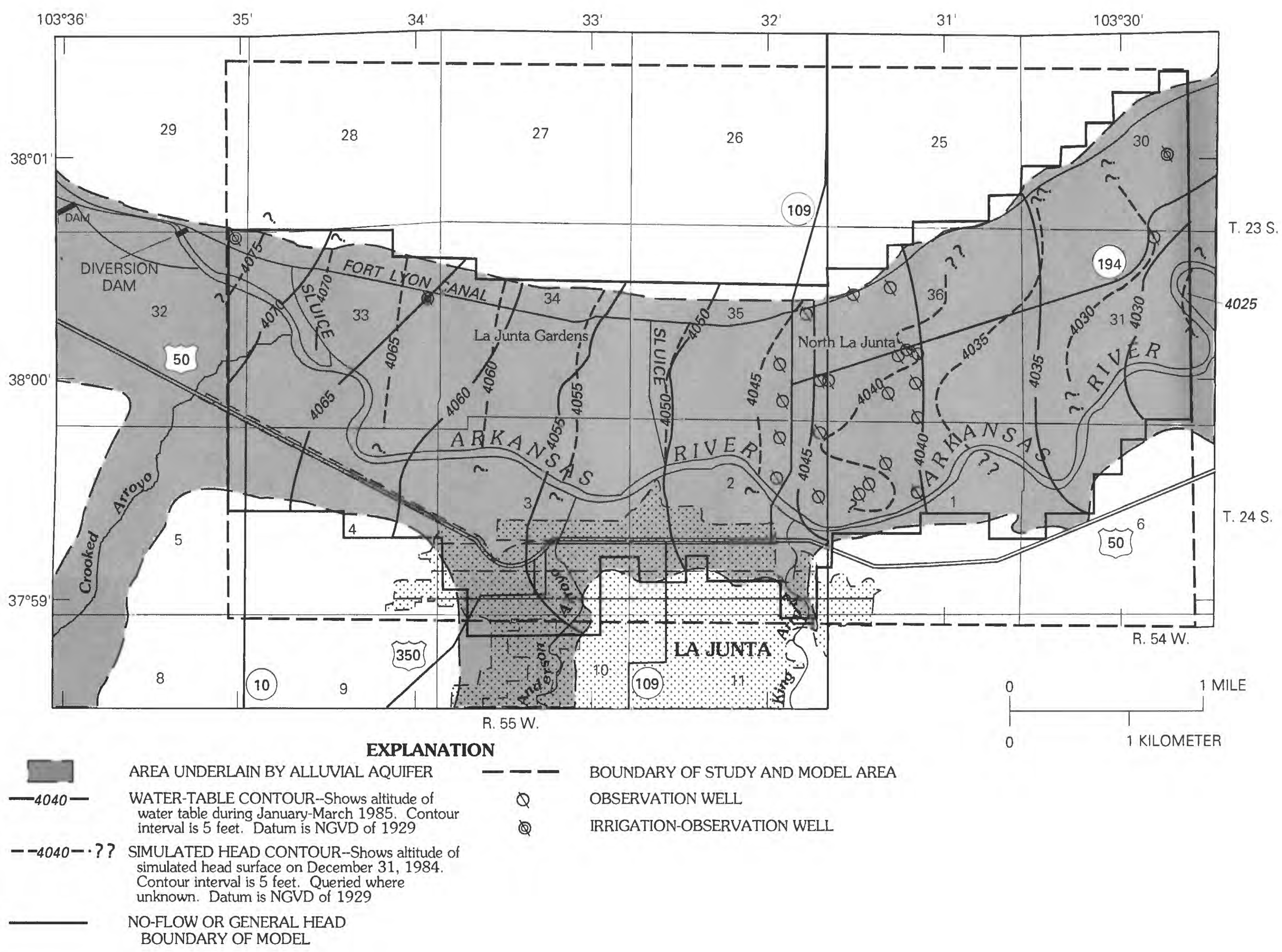

Figure 15.--Generalized altitude and configuration of the simulated head surface, December 31, 1984, and of the water table, January-March 1985.

Simulated storage change during April 1960-December 1979 was 142 acre-ft/yr and during January 1980-December 1984 was 498 acre-ft/yr. Assuming a specific yield of 0.20, the average rates of simulated water-level change (increase) equivalent to these storage changes are about 0.15 ft/yr for April 1960-December 1979 and 0.51 ft/yr for January 1980-December 1984. The generalized altitude and configuration of the simulated head surface on December 31, 1984, and of the water table based on measured water levels for January-March 1985 are shown in figure 15. Because the datum of the observation wells used in preparing the map of the water table were estimated from topographic maps with a contour interval of 2 ft, the water-table altitudes used in preparing the map were rounded to the nearest 2 ft.

EVALUATION OF POTENTIAL HYDROLOGIC EFFECTS OF THE FIVE PROPOSED WATER-MANAGEMENT ALTERNATIVES

The potential hydrologic effects of each of the five proposed water-management alternatives are evaluated based on the results of a numerical simulation of 1985-86 transient conditions. Initially, 1985-86 transient conditions were simulated to define the heads and ground-water budget that occurred without the proposed water-management alternatives; results from this simulation, which is referred to as the baseline model, are used for comparison with the results from simulations of the five water-management alternatives.

Changes were made to the input of the baseline model for the simulations of the five water-management alternatives. For alternative 1, the bed and stage of the river were simulated at altitudes 4 ft less than for the baseline model. For alternative 2, the bed of the Fort Lyon Canal was simulated to be impervious by setting the conductance of the bed to zero. For alternative 3, simulated municipal pumpage was increased by 50 percent. For alternative 4, a hypothetical network of 38 relief wells (fig. 16) was simulated to pump at a constant rate of 19,251 ft^3/d (100 gal/min) per well. For alternative 5, a hypothetical drainage system (fig. 17) was simulated with heads in the 38 drain nodes set at 10 ft below simulated land surface.

The effects of the five proposed water-management alternatives can be evaluated by comparing maps of water-level change and ground-water budgets. Maps of the simulated depth to water on December 31, 1986, for the baseline model and the alternatives are shown in figures 18-23. Maps of the simulated change in water levels from baseline conditions that result from the simulated alternatives are shown in figures 24-28. Simulated ground-water budgets are listed in table 4. Simulated depth-to-water contours, shown in figures 18-23, represent average values for 660-ft square grid cells and as such may not represent smaller-scale variations in the depth to water that would occur near the river channel.

Simulated heads in the baseline model continued to rise in response to the increased stages simulated for the canal and river and to a significant decrease in simulated pumpage. Storage was simulated to increase at about 699 acre-ft/yr, which is equivalent to an average rise in water level of about 0.72 ft/yr.

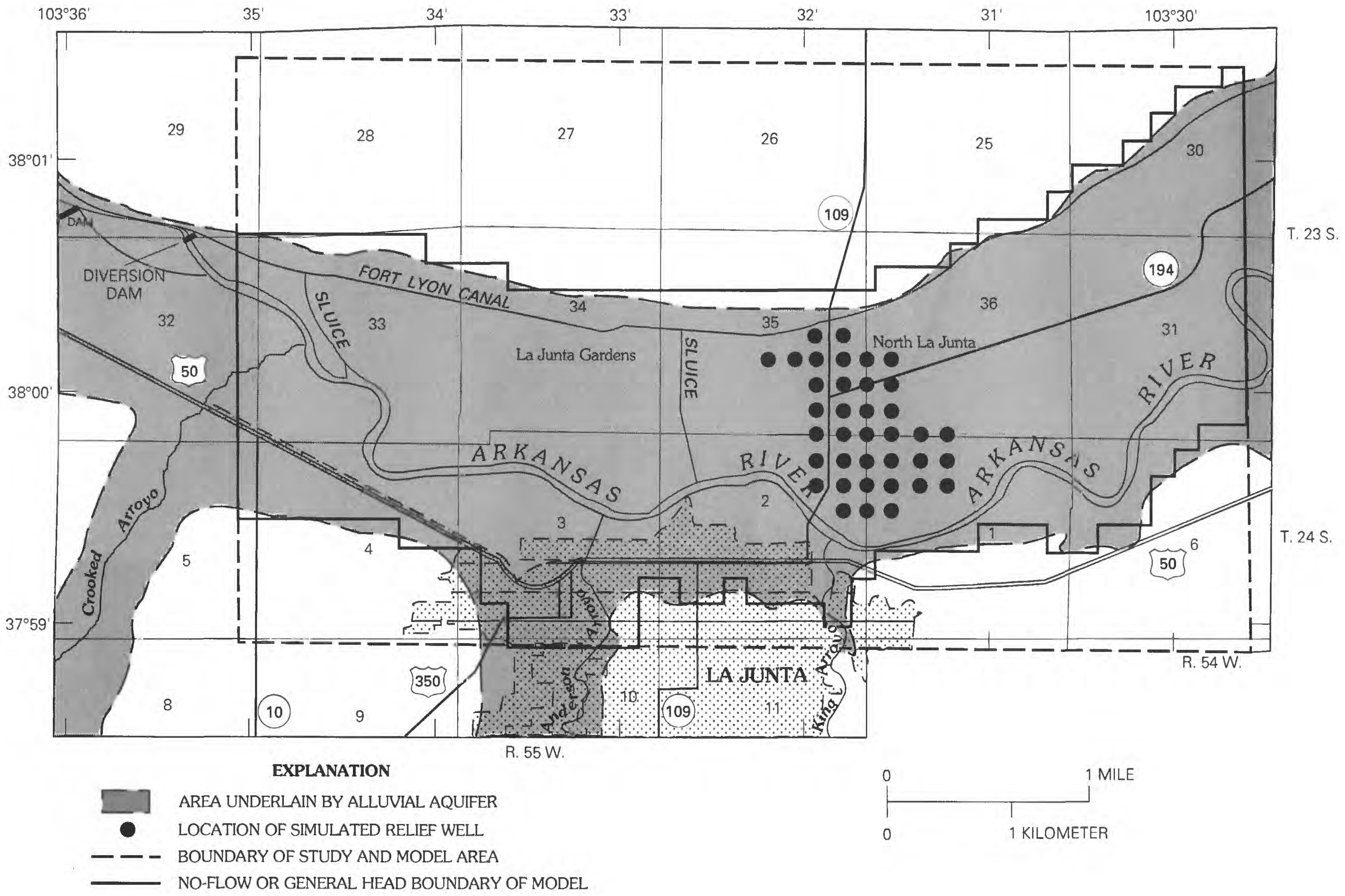

Figure 16.--Locations of simulated relief wells.

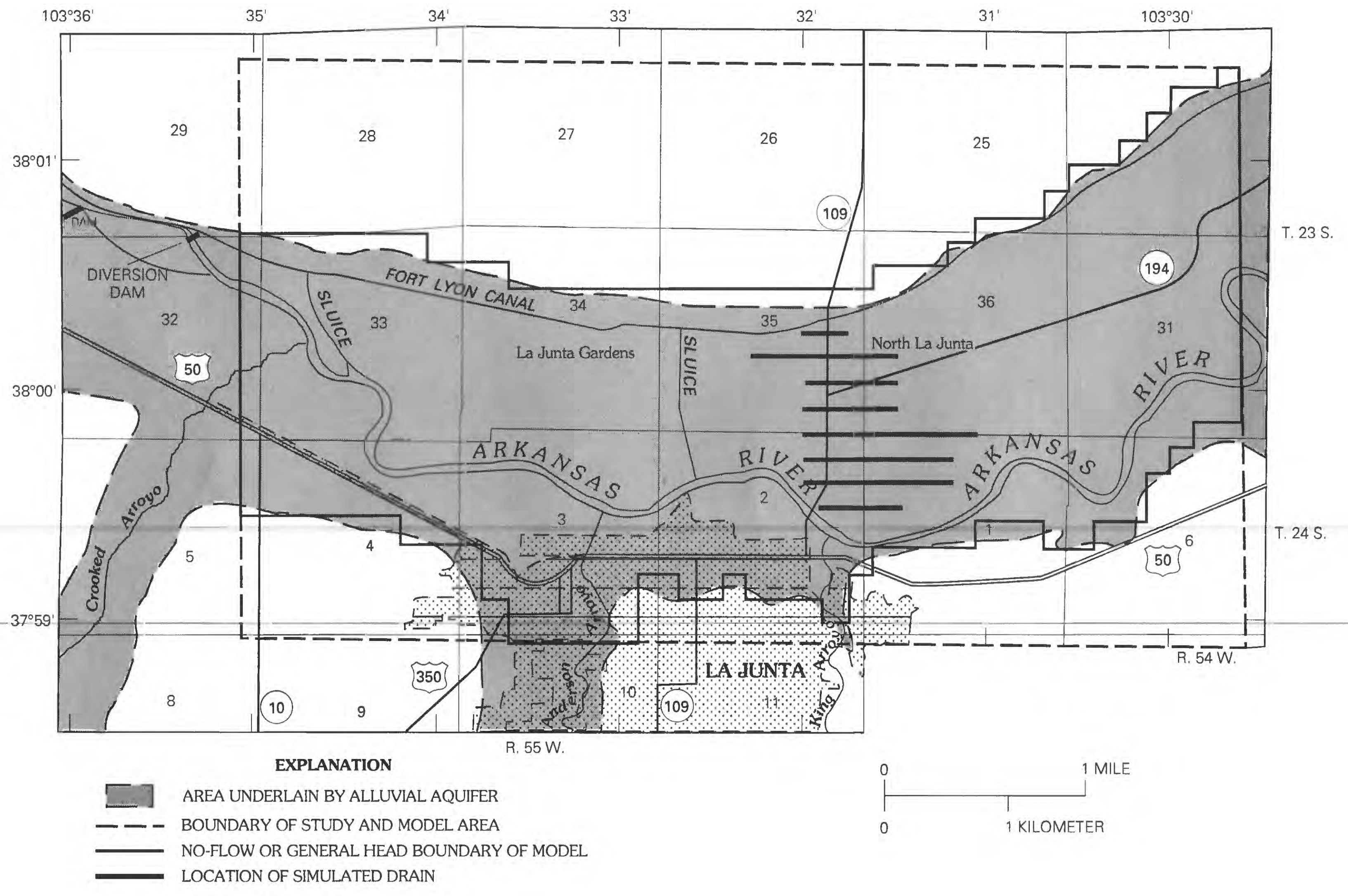

Figure 17.--Locations of simulated drains.

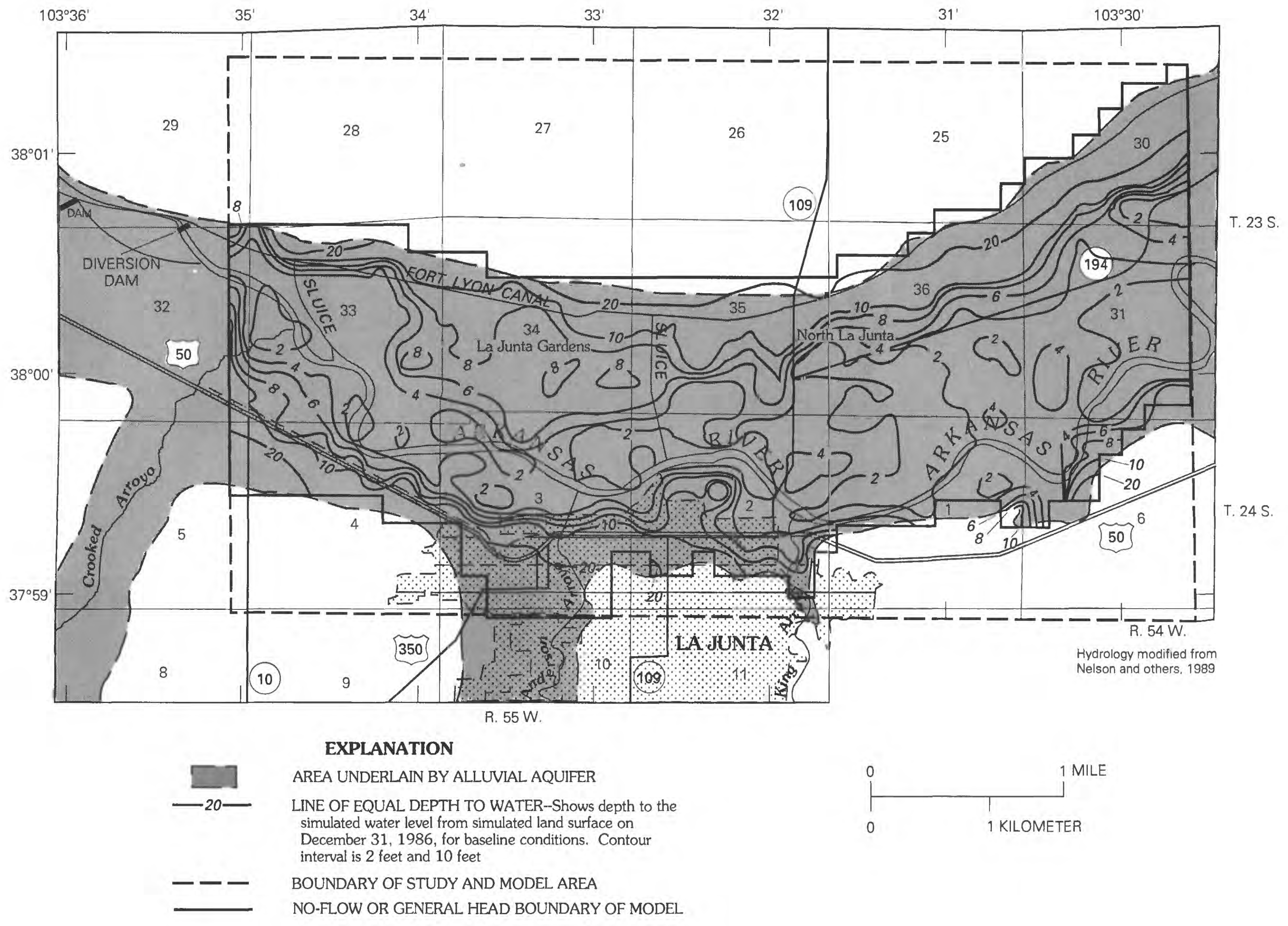

Figure 18.--Depth to simulated water level for the baseline model, December 31, 1986.

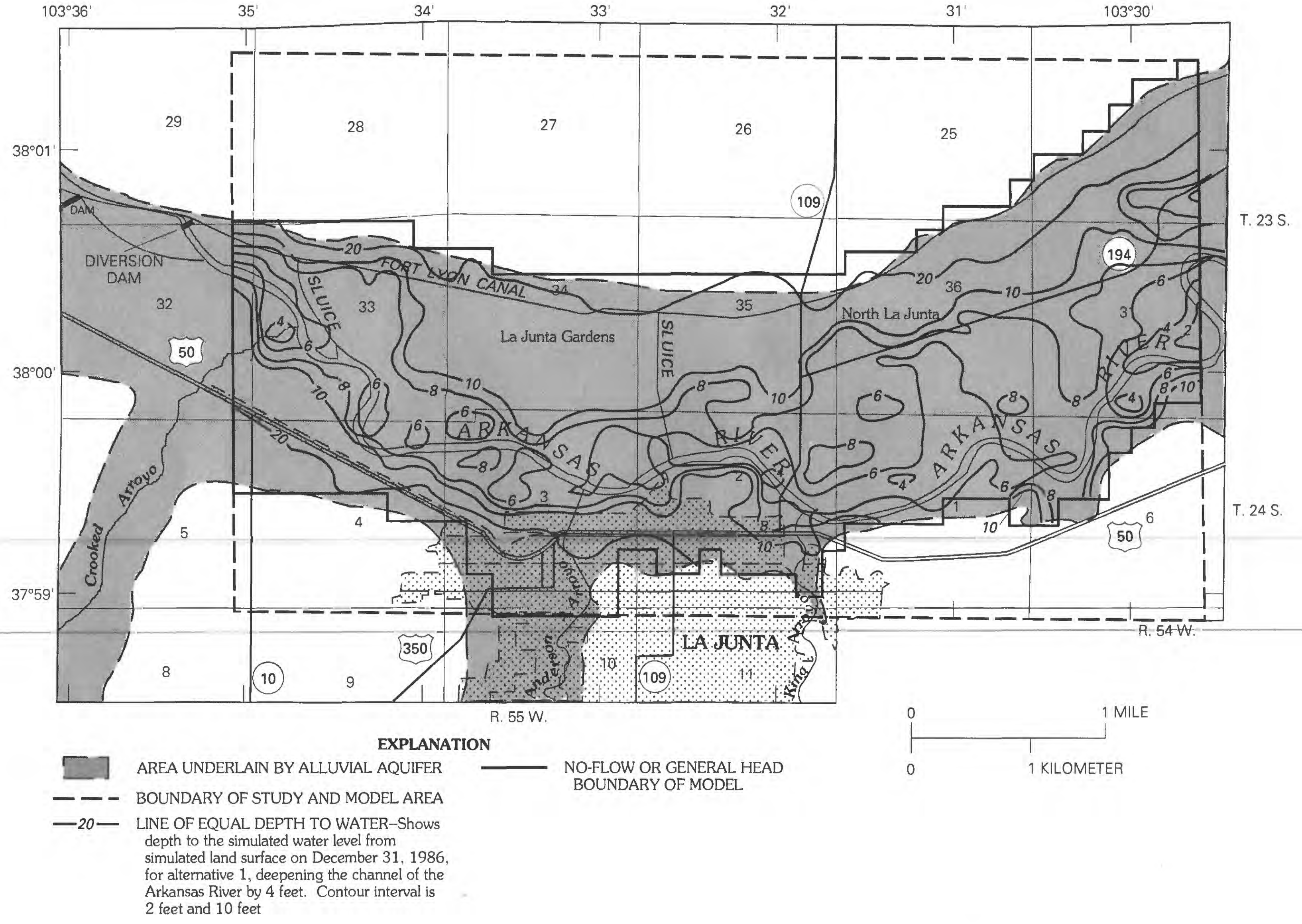

Figure 19.--Depth to simulated water level for alternative 1, deepening the channel of the Arkansas River by 4 feet, December 31, 1986.

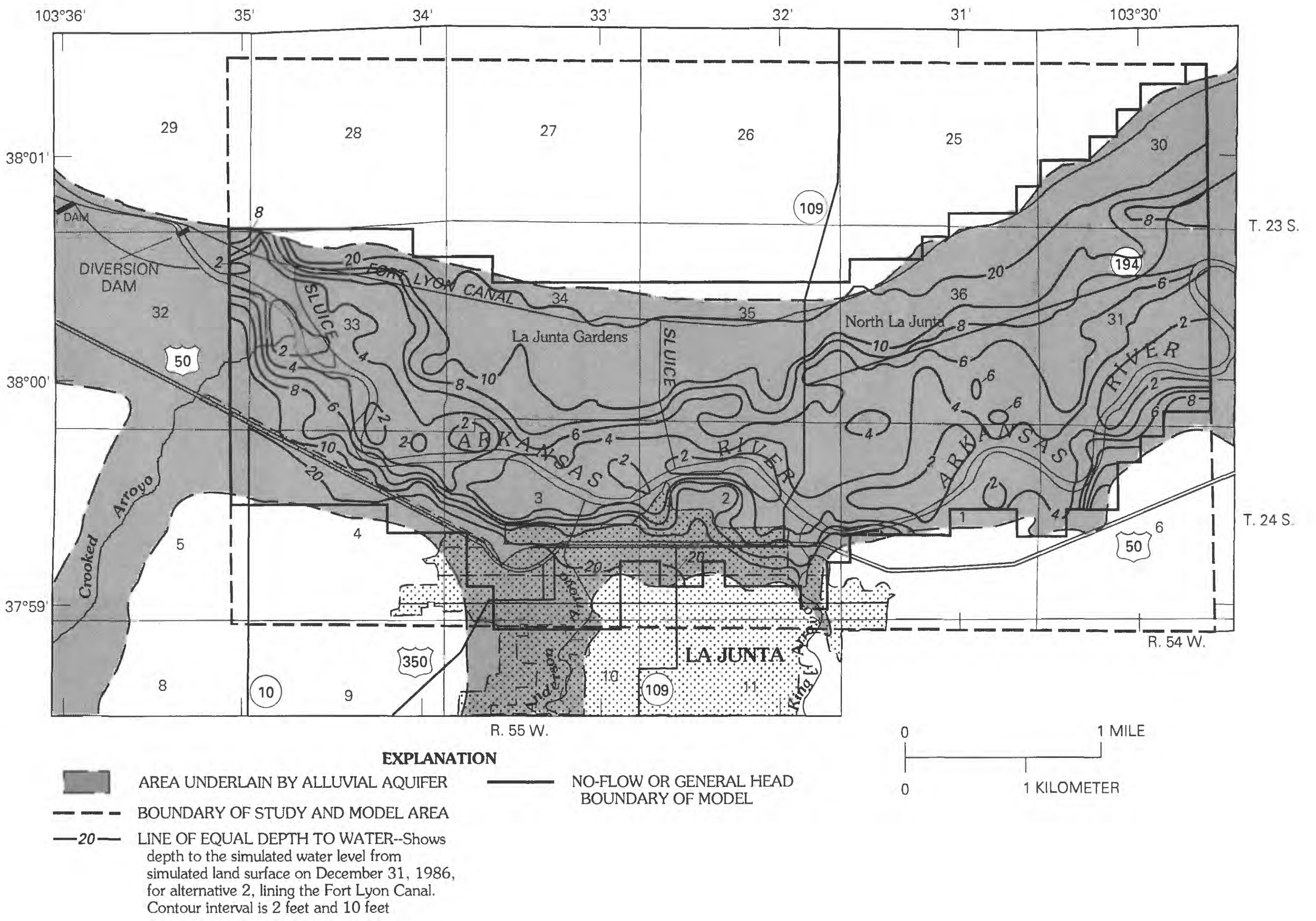

Figure 20.--Depth to simulated water level for alternative 2, lining the Fort Lyon Canal, December 31, 1986.

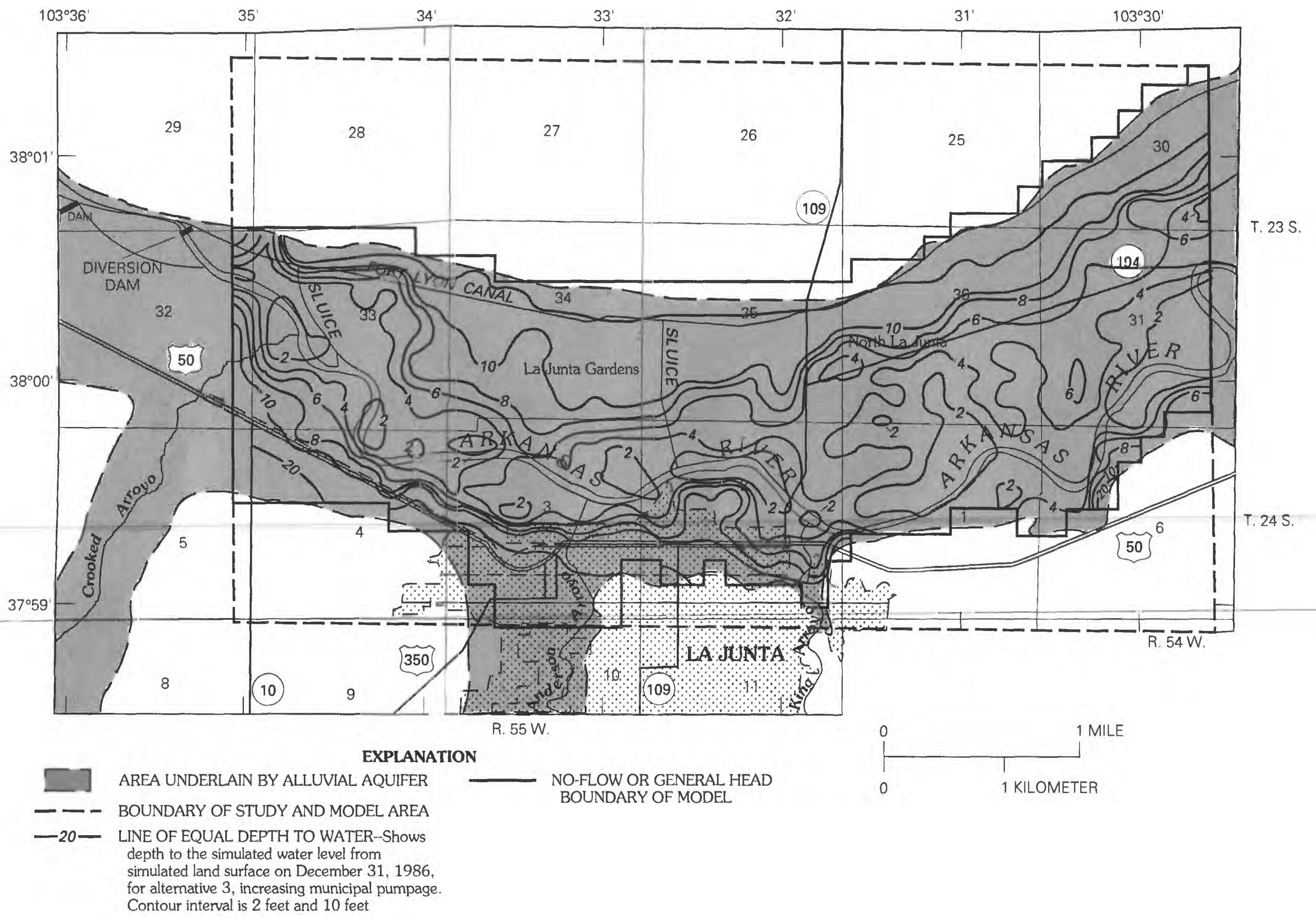

Figure 21.--Depth to simulated water level for alternative 3, increasing municipal pumpage, December 31, 1986.

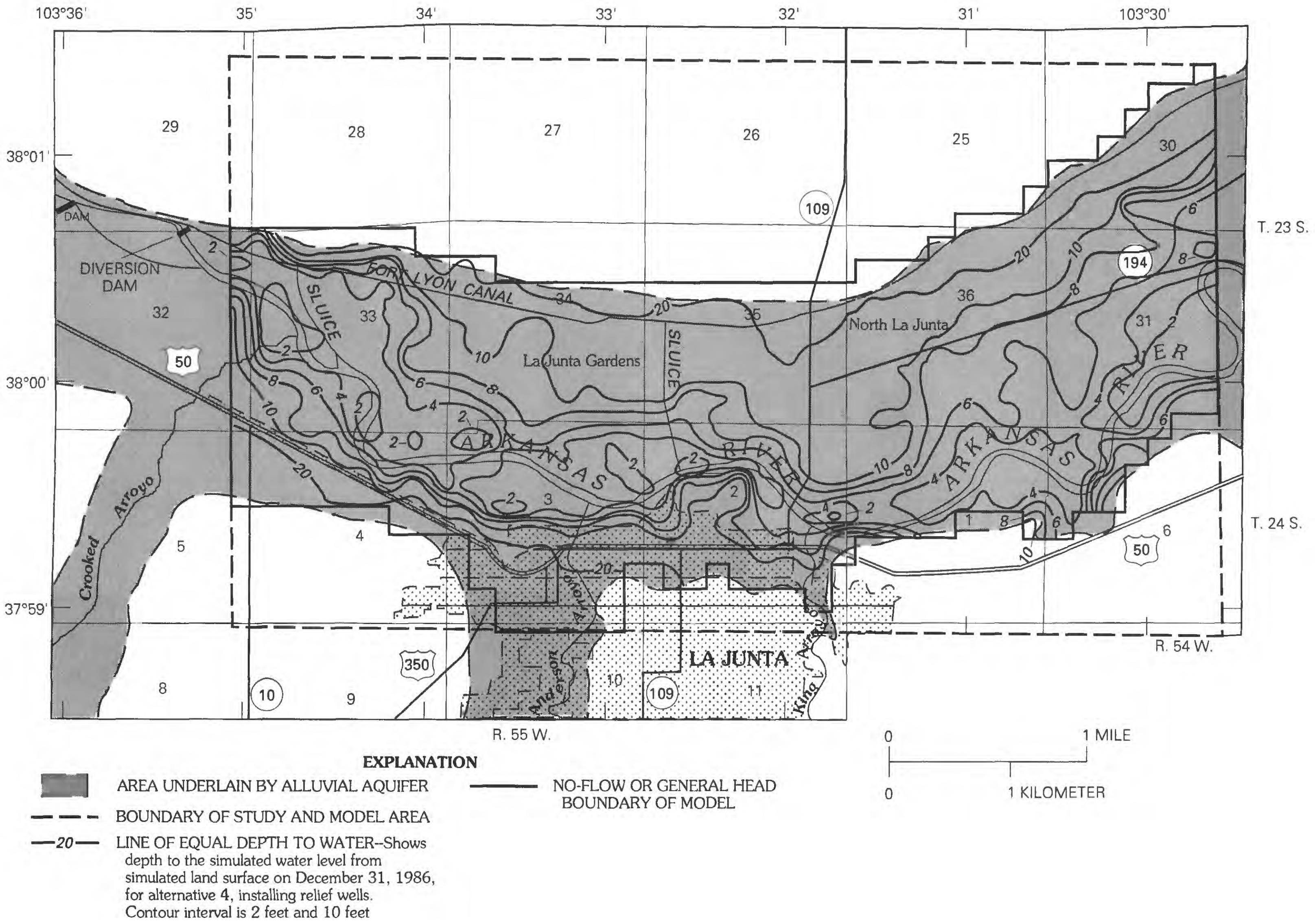

Figure 22.--Depth to simulated water level for alternative 4, installing relief wells, December 31, 1986.

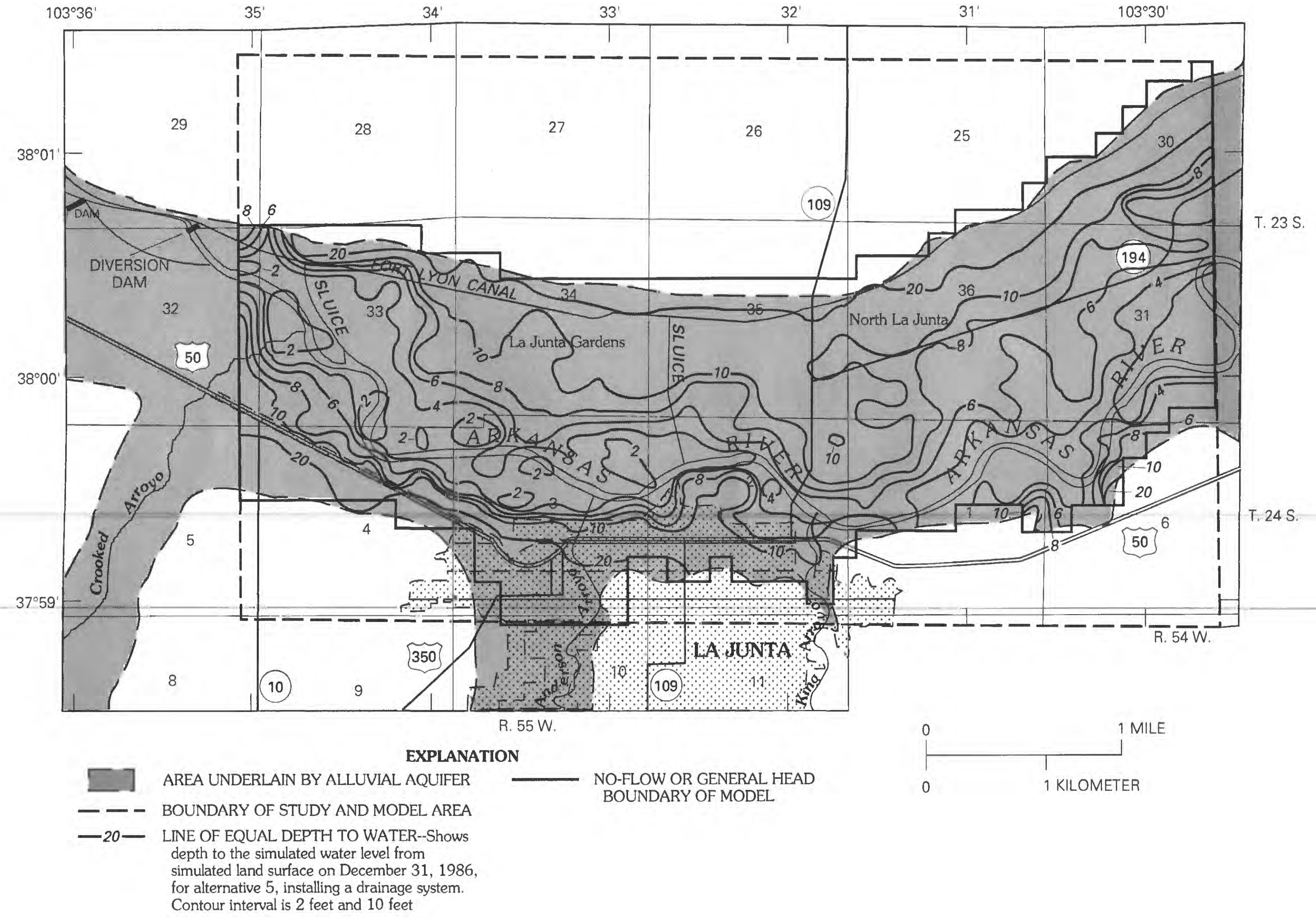

Figure 23.--Depth to simulated water level for alternative 5, installing a drainage system, December 31, 1986.

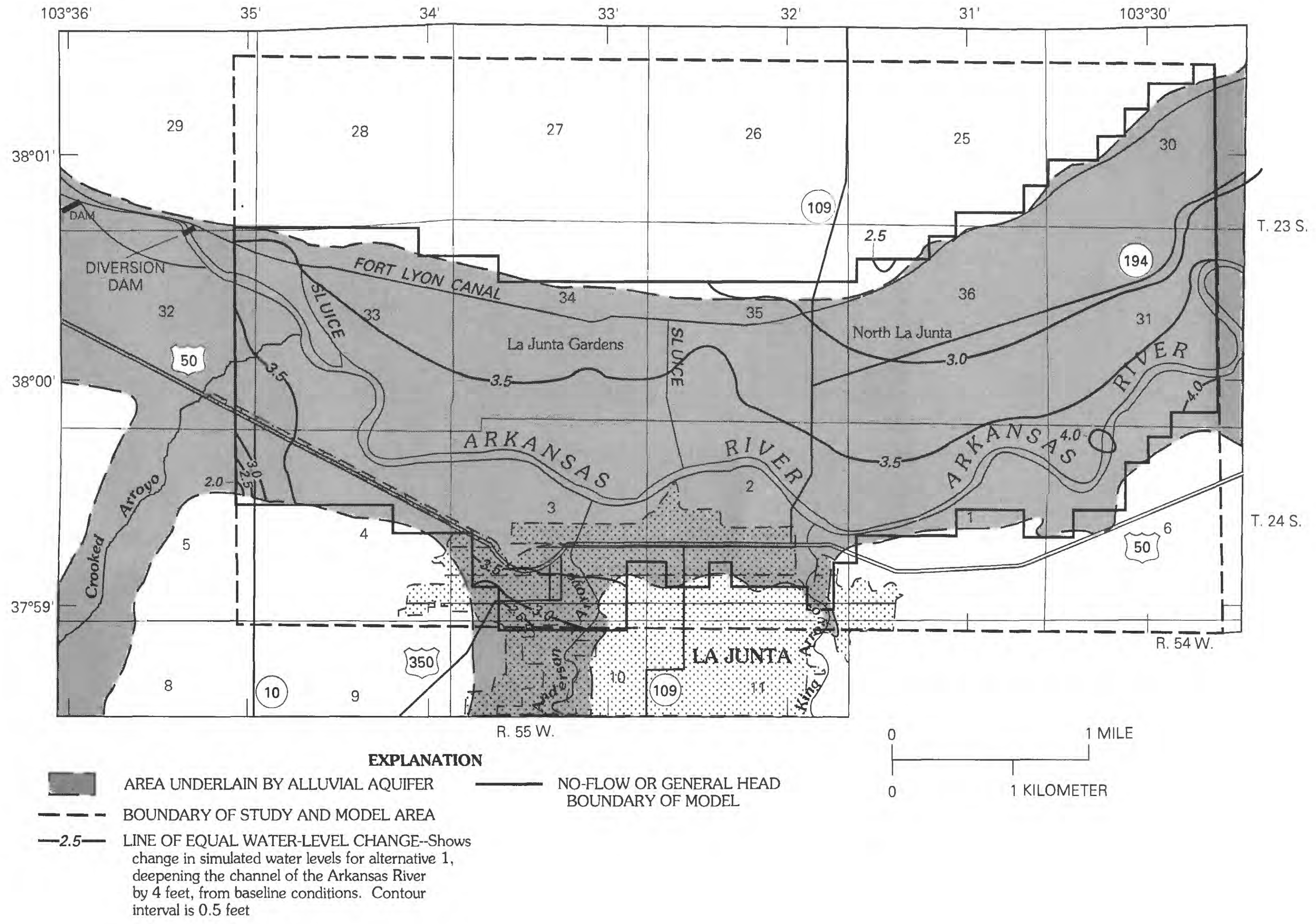

Figure 24.--Change in simulated water levels for alternative 1, deepening the channel of the Arkansas River by 4 feet.

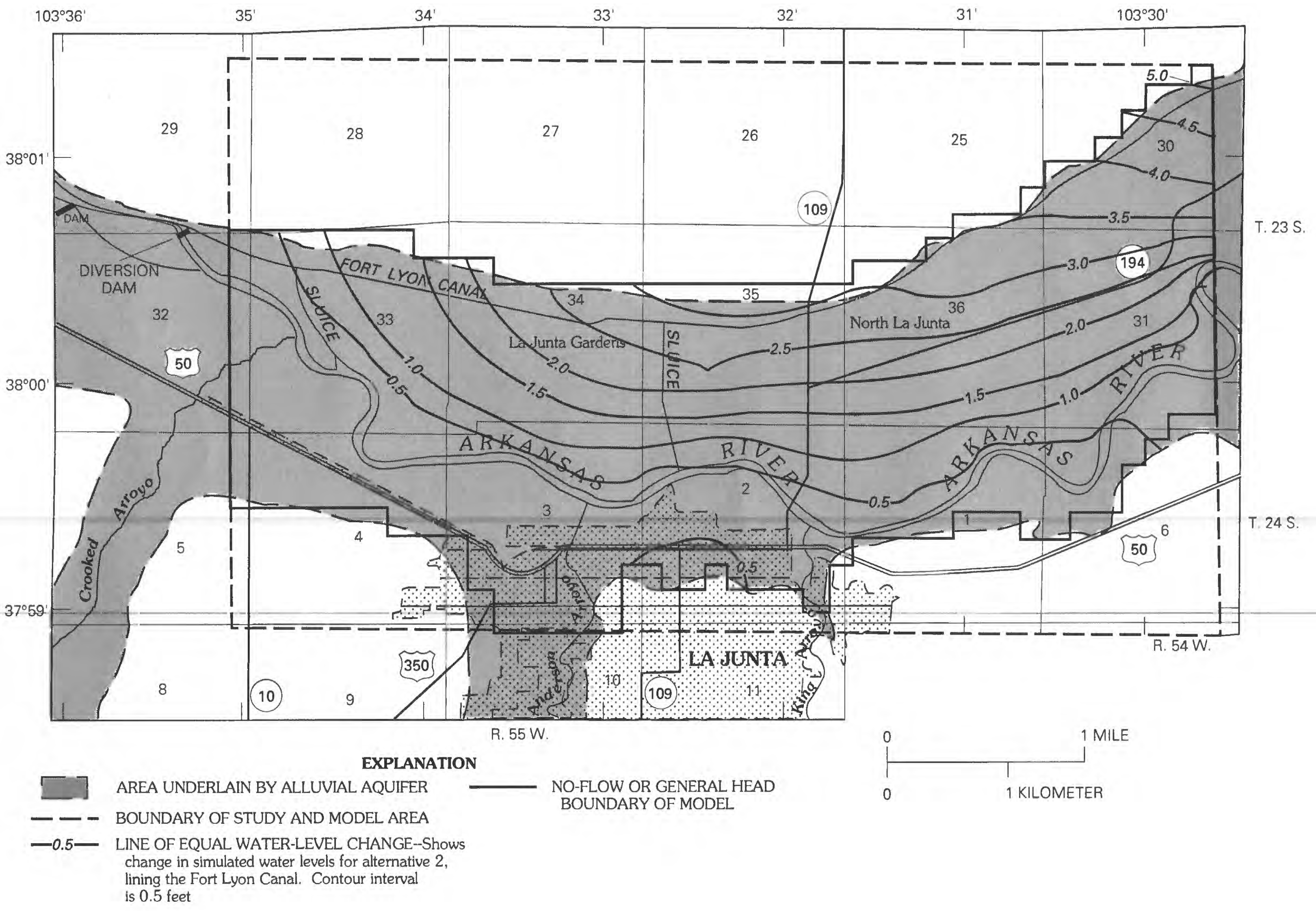

Figure 25.--Change in simulated water levels for alternative 2, lining the Fort Lyon Canal.

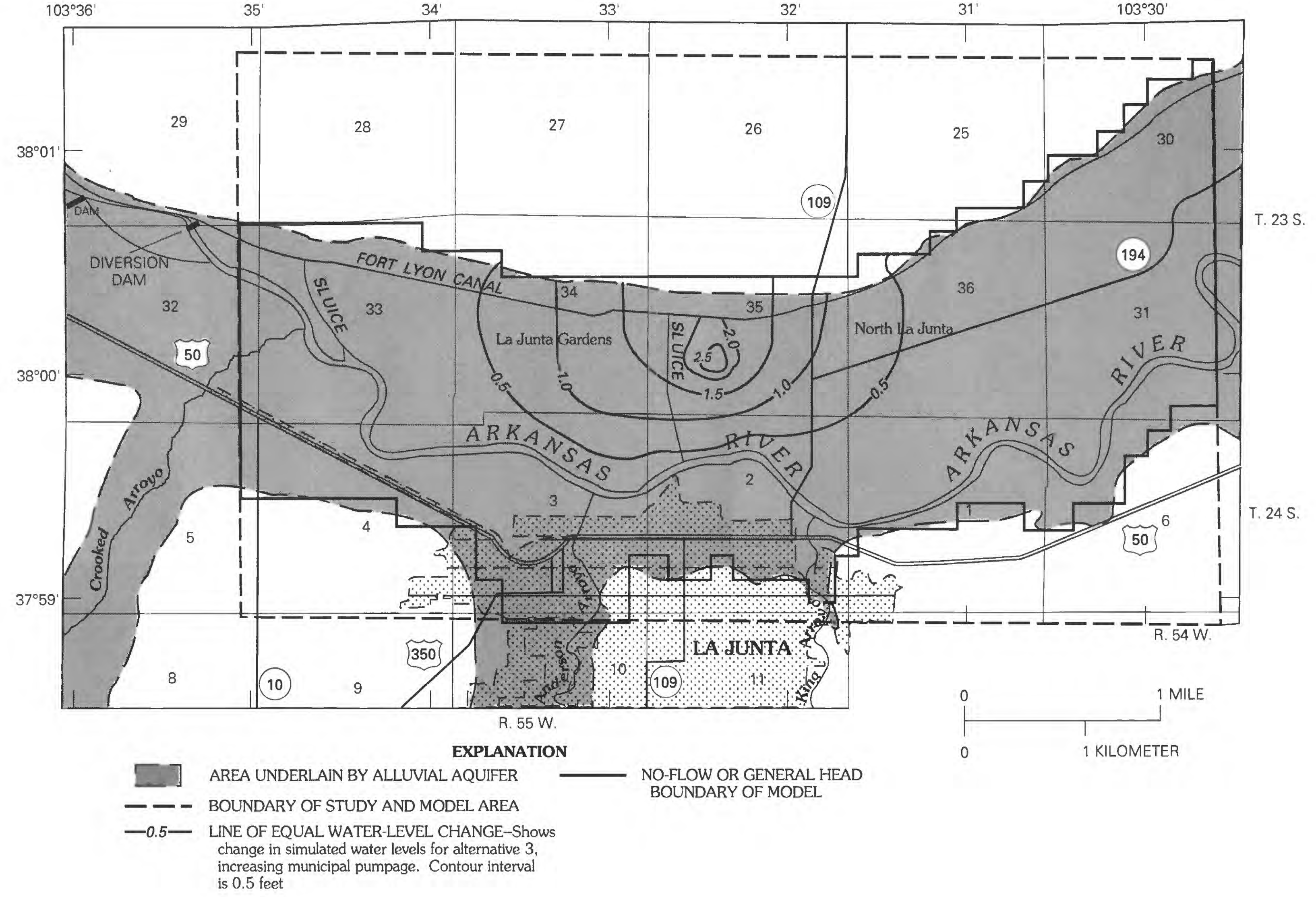

Figure 26.--Change in simulated water levels for alternative 3, increasing municipal pumpage.

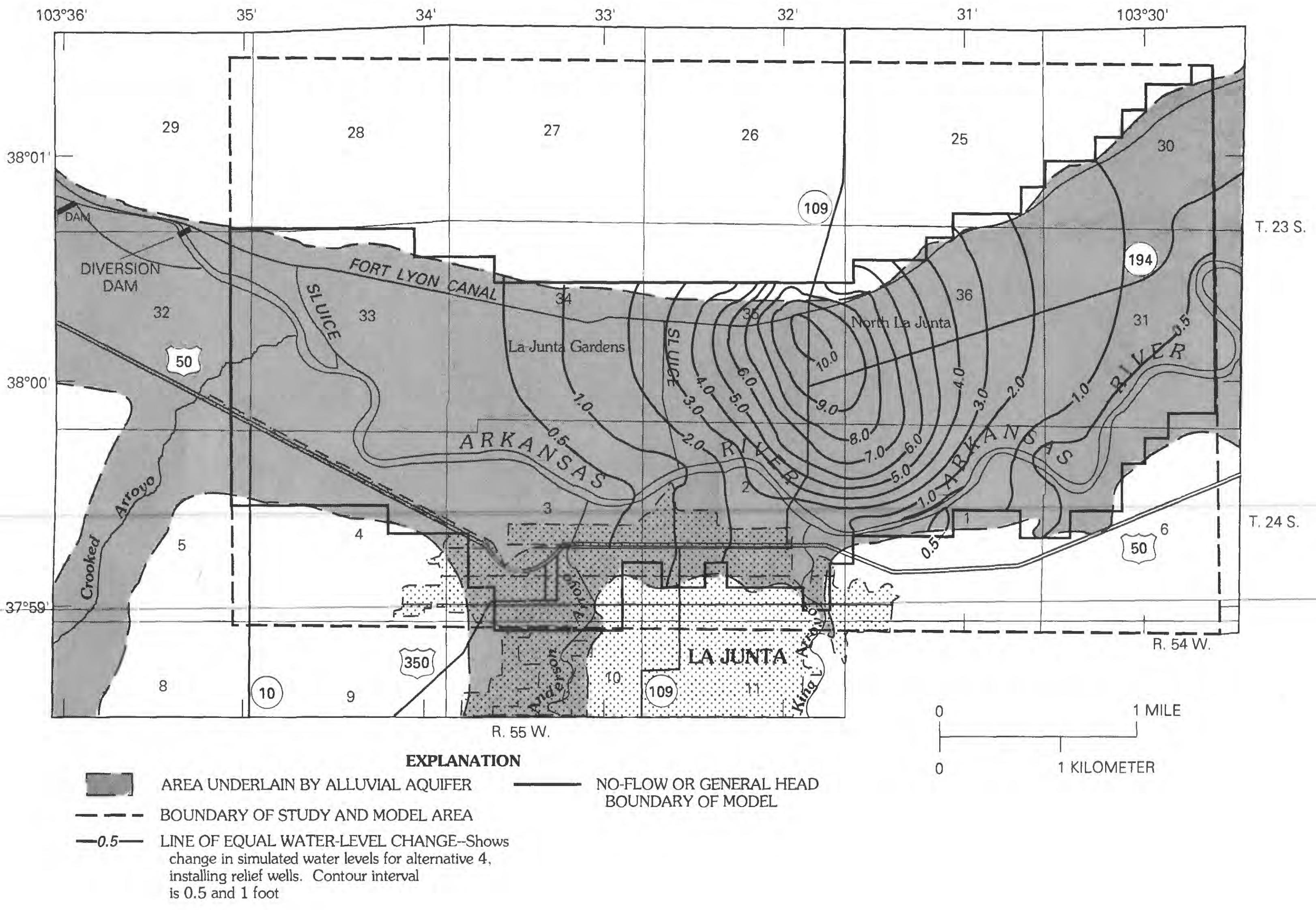

Figure 27.--Change in simulated water levels for alternative 4, installing relief wells.

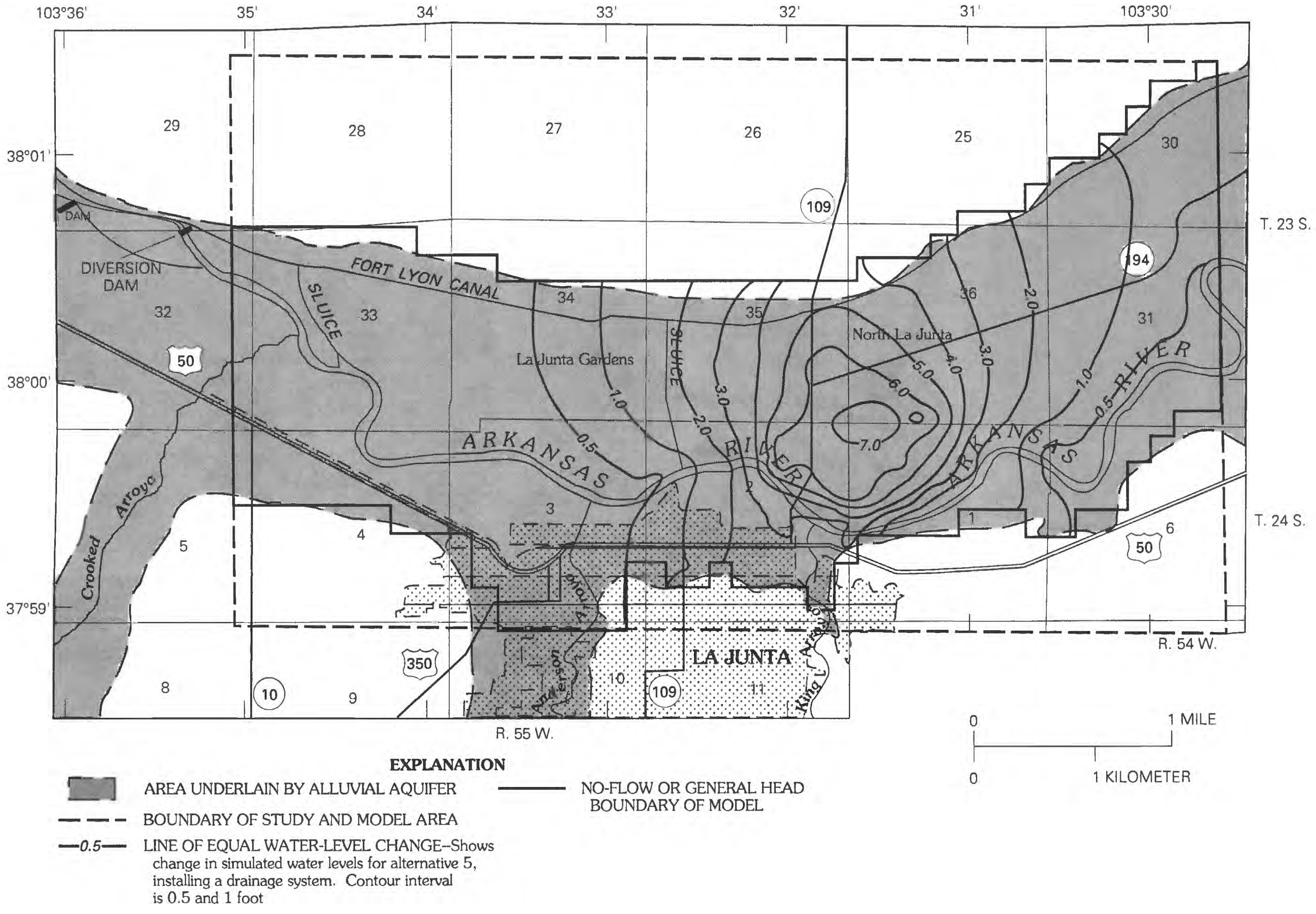

Figure 28.--Change in simulated water levels for alternative 5, installing a drainage system.

Table 4.--*Average annual simulated ground-water budgets and head changes for the baseline model and alternatives, 1985-86*

[All simulated budget values rounded to nearest acre-feet per year]

Simulation	Change to baseline mode	Ground-water budget											Head change[2]	
		Recharge				Discharge					Average[1] rate of storage change during 1985-86	Budget discrepancy (recharge minus discharge minus storage change)	Difference between median head change (feet)	Interquartile range (feet)
		Deep percolation	Leakage: Fort Lyon Canal	Leakage: Arkansas River	Underflow	Total pumpage	Flow to drains	Evapotranspiration	Leakage: Arkansas River	Underflow				
Baseline	None	2,824	5,888	3,653	1,599	4,573	0	5,967	2,276	1,845	699	2	--	1.9
Alternative 1	Deepening the channel of the Arkansas River.	2,824	5,898	1,533	1,782	4,583	0	3,151	5,202	1,782	-2,781	0	-5.2	1.3
Alternative 2	Lining the Fort Lyon Canal	2,824	0	6,257	1,613	4,573	0	4,755	1,145	1,791	-1,573	3	-2.7	3.7
Alternative 3	Increasing municipal pumpage.	2,824	5,889	4,395	1,600	5,952	0	5,709	2,124	1,845	-925	3	-1.9	2.4
Alternative 4	Installing relief wells.	2,824	5,891	6,977	1,600	10,703	0	4,783	1,828	1,838	-1,856	-4	-3.0	4.0
Alternative 5	Installing a drainage system.	2,824	5,891	8,046	1,600	4,573	7,487	4,411	1,723	1,835	-1,666	-2	-3.0	3.9

[1]Storage change, positive values indicate increase in storage; negative values indicate a decrease.
[2]Change in head calculated as final head minus initial head. Negative values indicate drawdown; positive values indicate a rise in head. The head difference resulting from simulation of an alternative is the difference between the median values for the alternative and the baseline model.

The simulated heads for alternative 1 (fig. 19), deepening the channel of the Arkansas River by 4 ft, declined about 4 ft, relative to baseline heads, throughout the study area (fig. 28). The difference in median values of head change between the baseline model and alternative-1 simulation was 5.2 ft (table 4). Head change for alternative 1 also had a relatively small interquartile range of 1.3 ft (table 4), indicating a fairly uniform decline in heads. Simulated net leakage was from the river at 1,377 acre-ft/yr for the baseline model and to the river at 3,669 acre-ft/yr for alternative 1. The difference in leakage between the baseline model and the alternative is about 5,046 acre-ft/yr. Storage decreased by 3,480 acre-ft/yr, relative to the baseline model (table 4). Simulated evapotranspiration also decreased by 2,816 acre-ft/yr relative to the baseline model.

The simulated heads for alternative 2 (fig. 20), lining the Fort Lyon Canal, declined about 5 ft near the canal, but almost no change in depth to water near the river was simulated (fig. 25). The simulated median head difference was -2.7 ft, with an interquartile range of 3.7 ft (table 4). Simulated net leakage from the river increased by 3,735 acre-ft/yr, relative to the baseline model (table 4). This alternative, while decreasing flow in the Arkansas River in this reach, would, in effect, increase the amount of water available for diversion from the Fort Lyon Canal by 5,888 acre-ft/yr. Simulated storage decreased by 2,272 acre-ft/yr and simulated evapotranspiration decreased by 1,212 acre-ft/yr, relative to the baseline model.

The simulated heads for alternative 3 (fig. 21), increasing municipal pumpage by 50 percent, had relatively small localized water-level declines (fig. 26). A simulated 50-percent increase in municipal pumpage (a 1,379-acre-ft/yr increase in total pumpage) resulted in an 894-acre-ft/yr increase in net leakage from the river, a 258-acre-ft/yr decrease in evapotranspiration, and only a 226-acre-ft/yr decrease in storage, relative to baseline conditions. The median value of head difference from baseline conditions was a -1.9 ft.

The simulated heads for alternative 4 (fig. 22), installing relief wells, locally, near the center of the hypothetical well field, decreased about 8 to 10 ft relative to the heads for the baseline model (fig. 27). A simulated increase in total pumpage of 6,130 acre-ft/yr produced a 2,555-acre-ft/yr decrease in storage relative to the baseline model (table 4). The simulated increase in pumpage also caused an increase in net leakage from the river of 3,772 acre-ft/yr and a decrease in evapotranspiration of 1,184 acre-ft/yr, when compared to the baseline model (table 4). The water pumped by the relief wells, if returned to the river downstream from the study area, would increase flow in the river relative to baseline conditions.

The simulated heads for alternative 5 (fig. 23), installing a drainage system, decreased near the center of the drainage system by about 7 ft relative to the baseline model (fig. 28). Because the hydraulic gradient of the water table and slope of the land surface in the valley are relatively low, collector wells probably would be needed to remove water from the drains for discharge to some point downstream from the study area. The drainage system increased simulated net leakage from the river by about 4,946 acre-ft/yr, when compared to the baseline model (table 4), but the 7,487 acre-ft/yr removed by the drains would be available for return to the river. The simulated decrease of storage was 2,365 acre-ft/yr and of evapotranspiration was 1,556 acre-ft/yr, relative to the baseline model.

The accuracy of the simulations of the water-management alternatives are limited by several factors. The transient model was calibrated for generalized estimates of monthly recharge and discharge that can not be verified at specific sites; therefore, the model is a generalized approximation of the real system. Because the model calculates heads at nodes that are on 660-ft centers, the model cannot be used to predict the heads between nodes in areas where the aquifer is strongly stressed. For example, in alternative 5, in which drains are simulated in all contiguous grid blocks in a specified area, hydraulic gradients between the simulated drains cannot be predicted. The model can only predict average heads for 10-acre areas. The effects of short-term, less than monthly, variations in specified constant fluxes (for example, pumpage) or in head-dependent fluxes (for example, river and canal stage) were not evaluated. Economic, engineering, and legal aspects of implementing the proposed water-management alternatives were not considered in the simulation of the hypothetical hydrologic effects of the alternatives.

SUMMARY

The water table in the alluvial aquifer in the Arkansas River valley near La Junta, Colorado, rose during the early 1980's. The rising water table caused flooding of basements, damage to some homes, and the water-logging of some cropland. The rise in the water table was caused by a combination of factors, but was due primarily to increased leakage from the Arkansas River and Fort Lyon Canal and decreased ground-water pumpage for irrigation. An important factor affecting the water table is aggradation of the Arkansas River bed and accompanying rise in river stage, which temporarily increases leakage from the river and increases long-term storage in the aquifer; however, the causes of aggradation of the river bed were not investigated during this study.

A numerical, two-dimensional model of steady-state ground-water flow was used to test the sensitivity of the system to errors in the estimates of hydraulic properties and specified recharge and discharge conditions. Steady-state ground-water budgets and heads were sensitive to the altitude of the river bed, ground-water pumpage for irrigation and industrial supply, the conductance of the Fort Lyon Canal bed, deep percolation of irrigation water and precipitation, and evapotranspiration. The model was calibrated for April 1960-December 1984 transient conditions and used to evaluate the potential hydrologic effects of five water-management alternatives that had been proposed to lower the water table.

The five proposed water-management alternatives evaluated for 1985-86 transient conditions were: (1) Deepening the channel of the Arkansas River, (2) lining the Fort Lyon Canal, (3) increasing municipal pumpage, (4) installing relief wells, and (5) installing a drainage system. Comparisons between simulated water-level change and ground-water budgets were made for each of the alternatives. Model simulations of the various alternatives indicated that: (1) Deepening the channel of the Arkansas River by 4 ft would decrease the water-table altitudes about 4 feet in the study area, and as a result of the simulated change of hydraulic gradient between the aquifer and the river, net leakage to the river was simulated as 3,669 acre-ft/yr; (2) lining the Fort Lyon Canal would lower the water table by about 5 ft near the canal but would cause little change in the depth to water near the river; (3) increasing municipal pumpage by 1,379 acre-ft/yr would cause only localized changes in the water table near the three municipal well fields and would increase leakage from the river by 894 acre-ft/yr; (4) installing relief wells would produce relatively large but localized declines in the water table and would increase leakage from the river by 3,772 acre-ft/yr; and (5) installing a drainage system also would produce relatively large but localized declines in the water table and would increase leakage from the river by 4,946 acre-ft/yr.

The accuracy of the results from the model is limited by the accuracy of the estimated recharge and discharge conditions used in calibration of the model and by the inability to simulate heads between nodes in strongly stressed areas. Better estimates of ground-water pumpage for irrigation, of deep percolation from irrigated land, of ground-water evapotranspiration, and of conductance of the riverbed and canal bed would enable more realistic simulation of the stream-aquifer system. Knowledge of the processes and factors affecting aggradation of the river bed are needed to determine potential effects on ground-water flow and storage.

SELECTED REFERENCES

Buchanan, T.J., and Somers, W.P., 1969, Discharge measurements at gaging stations--Applications of hydraulics: U.S. Geological Survey Techniques of Water-Resources Investigations, bk. 3, chap. A8, 65 p.

Cain, Doug, 1985, Quality of the Arkansas River and irrigation-return flows in the lower Arkansas River valley, Colorado: U.S. Geological Survey Water-Resources Investigations Report 84-4273, 85 p.

Franke, O.L., Reilly, T.E., and Bennett, G.D., 1987, Definition of boundary and initial conditions in the analysis of saturated ground-water flow systems--An introduction: U.S. Geological Survey Techniques of Water-Resources Investigations, bk. 3, chap. B5, 15 p.

Hendricks, E.L., 1962, Surface water supply of the United States--1960: U.S. Geological Survey Water-Supply Paper 1711, 594 p.
Kilpatrick, F.A., 1965, Use of flumes in measuring discharge at gaging stations: U.S. Geological Survey Techniques of Water Resources Investigations, bk. 1, chap. 16, 27 p.
Konikow, L.F., and Bredehoeft, J.D., 1973, Simulation of hydrologic and chemical-quality variations in an irrigated stream-aquifer system: Colorado Water Resources Circular 17, 43 p.
_____1974, Modeling flow and chemical quality changes in an irrigated stream-aquifer system: Water Resources Research, v. 10, no. 3, p. 546-562.
Konikow, L.F., and Person, Mark, 1985, Assessment of long-term salinity changes in an irrigated stream-aquifer system: Water Resources Research, v. 21, no. 11, p. 1611-1624.
Lohman, S.W., and others, 1972, Definitions of selected ground-water terms--revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.
Major, T.J., Hurr, R.T., and Moore, J.E., 1970, Hydrogeologic data for the lower Arkansas River valley, Colorado: Colorado Basic Data Release 21, 125 p.
McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water Resources Investigations, bk. 6, chap. A1, 576 p.
Moore, J.E., and Jenkins, C.T., 1966, An evaluation of the effect of ground-water pumpage on the infiltraiton of a semipervious streambed: Water Resources Research, v. 2, no. 4, p. 691-696.
Moore, J.E., and Wood, L.A., 1967, Data requirements and preliminary results of an analog-model evaluation--Arkansas River valley in eastern Colorado: Ground Water, v. 5, no. 1, p. 20-23.
National Oceanic and Atmospheric Administration, 1986, Climatological data annual summary Colorado: Asheville, NC, National Climatic Data Center, v. 91, no. 13, 36 p.
Nelson, G.A., Hurr, R.T., and Moore, J.E., 1989, Hydrogeologic characteristics of the valley-fill aquifer in the Arkansas River valley, Crowley and Otero Counties, Colorado: U.S. Geological Survey Open-File Report 89-255, 3 sheets.
Rantz, S.E., and others, 1982, Measurement and computation of streamflow: U.S. Geological Survey Water-Supply Paper 2175, v. 2, p. 285-631.
Taylor, O.J., and Luckey, R.R., 1972, A new technique for estimating recharge using a digital model: Ground Water, v. 10, no. 6, p. 22-26.
U.S. Army Corps of Engineers, 1977, Special flood hazard information--Arkansas River, Anderson and King Arroyos, La Junta, Otero County, Colorado: Albuquerque, 29 p.
U.S. Department of the Interior, U.S. Bureau of Reclamation, 1978, Drainage Manual: U.S. Government Printing Office, 286 p.
Weeks, E.P., and Sorey, M.L., 1973, Use of finite-difference arrays of observation wells to estimate evapotranspiration from ground water in the Arkansas River valley, Colorado: U.S. Geological Survey Water-Supply Paper 2029-C, p. C1-C27.
Weist, W.G. Jr., 1965, Geology and occurrence of ground water in Otero County and the southern part of Crowley County, Colorado: U.S. Geological Survey Water-Supply Paper 1799, 90 p.

SUPPLEMENTAL INFORMATION

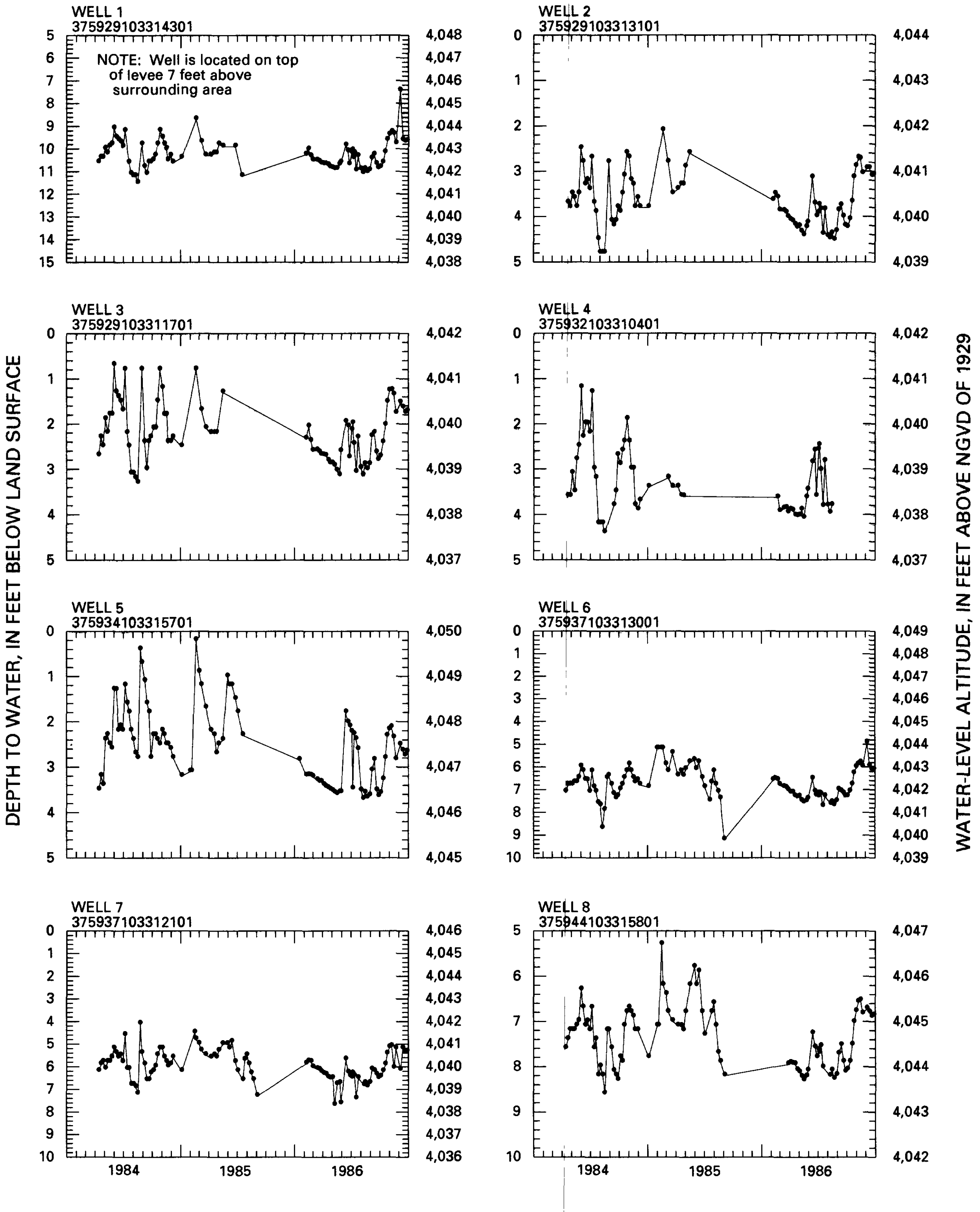

Figure 29.--Depth to water at selected observation wells, 1984-86. The 15-digit number following the well designation is the U.S. Geological Survey site-identification number. The lines connecting data points do not represent intermediate values and only are shown to indicate trends. Datum for wells was estimated from topographic maps with a 2-foot contour interval (U.S. Army Corps of Engineers, 1977).

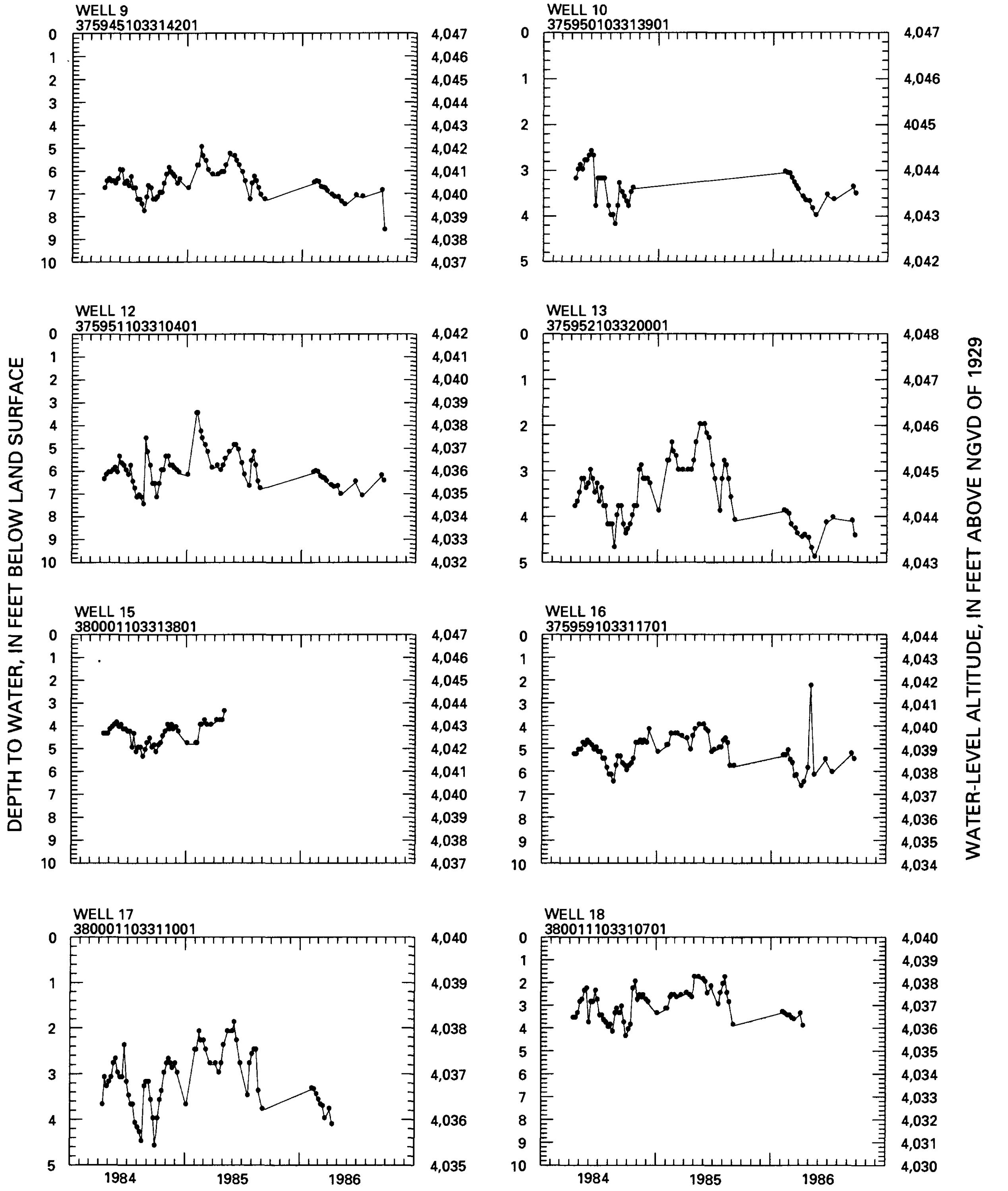

Figure 29.--Depth to water at selected observation wells, 1984-86. The 15-digit number following the well designation is the U.S. Geological Survey site-identification number. The lines connecting data points do not represent intermediate values and only are shown to indicate trends. Datum for wells was estimated from topographic maps with a 2-foot contour interval (U.S. Army Corps of Engineers, 1977)--Continued.

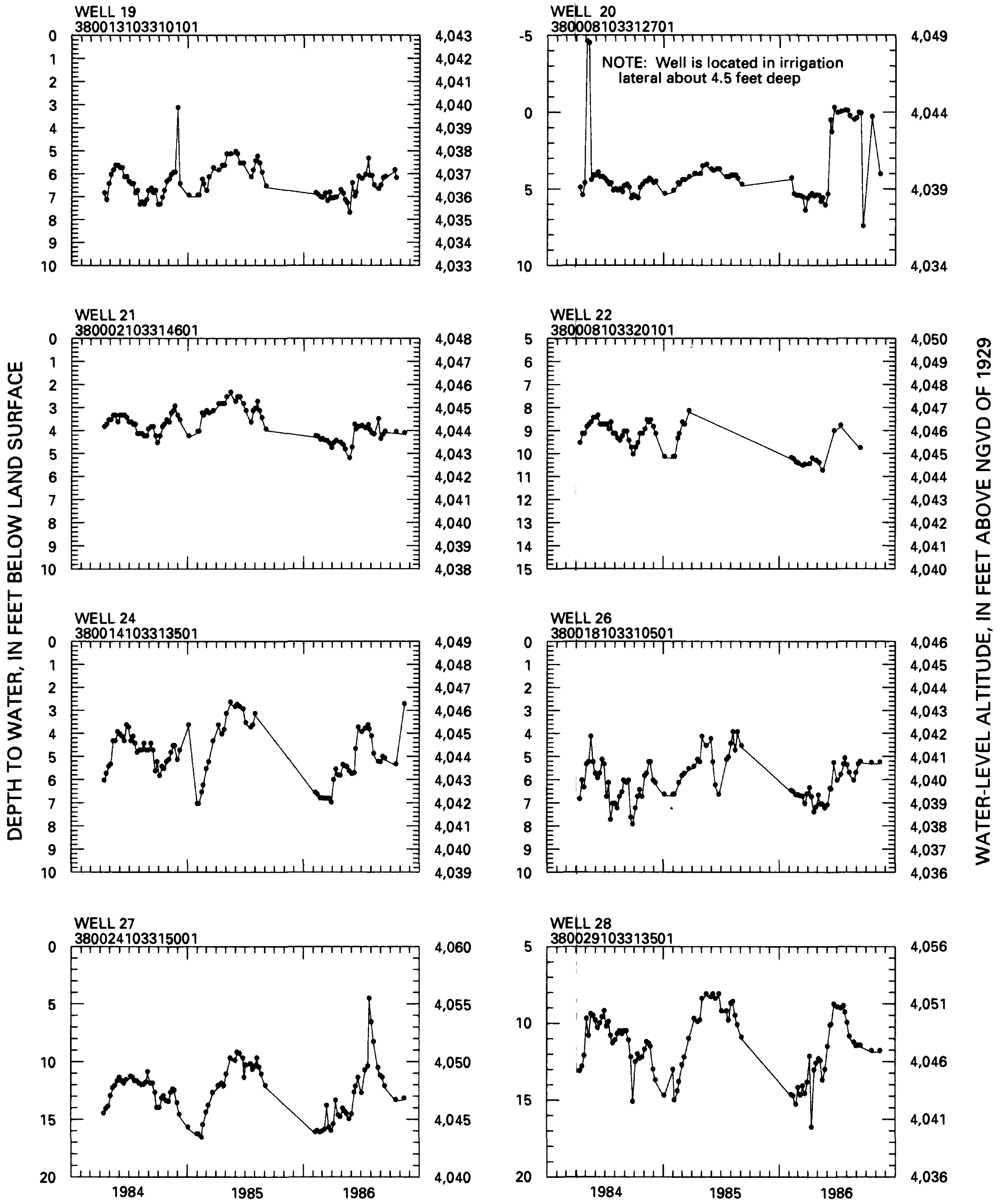

Figure 29.--Depth to water at selected observation wells, 1984-86. The 15-digit number following the well designation is the U.S. Geological Survey site-identification number. The lines connecting data points do not represent intermediate values and only are shown to indicate trends. Datum for wells was estimated from topographic maps with a 2-foot contour interval (U.S. Army Corps of Engineers, 1977)--Continued.

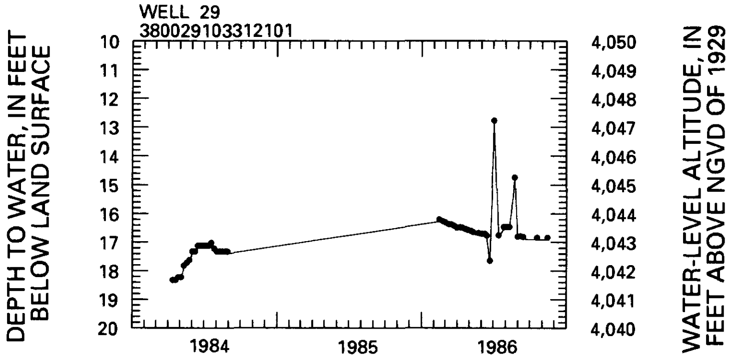

Figure 29.--Depth to water at selected observation wells, 1984-86. The 15-digit number following the well designation is the U.S. Geological Survey site-identification number. The lines connecting data points do not represent intermediate values and only are shown to indicate trends. Datum for wells was estimated from topographic maps with a 2-foot contour interval (U.S. Army Corps of Engineers, 1977)--Continued.

U.S. GOVERNMENT PRINTING OFFICE 1992-0-673-207/50036