Numerical Simulation of Ground-Water Flow and Assessment of the Effects of Artificial Recharge in the Rialto–Colton Basin, San Bernardino County, California

By Linda R. Woolfenden *and* Kathryn M. Koczot

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Conversion Factors

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
Area		
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer
Volume		
acre-foot (acre-ft)	1,233	cubic meter
acre-foot (acre-ft)	0.001233	cubic hectometer
Flow rate		
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
foot per second (ft/s)	0.3048	meter per second
foot per day (ft/d)	0.3048	meter per day
feet per year (ft/yr)	111.252	meters per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch per year (in/yr)	25.4	millimeter per year
square foot per second (ft^2/s)	0.0929	square meter per second
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day
Leakance		
foot per day per foot [(ft/d)/ft]	1	meter per day per meter

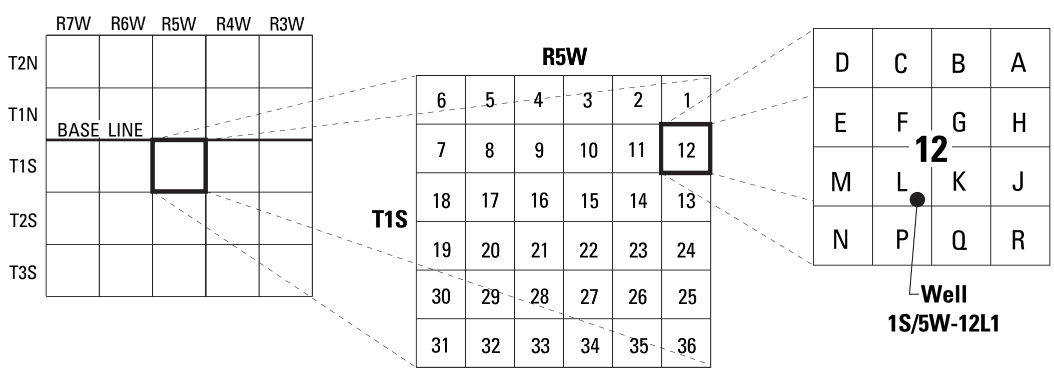
Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviations and Definitions

ADAPS	Automated Data Processing System
AML	Arc Macro Language
ARC-INFO	Geographic information system (GIS) software developed by Environmental Systems Research Institute, Inc. (ESRI), Redlands, California
DEM	Digital evaluation model
GWSI	Grooound-Water Site Inventory System
HFB Package	Horizontal-flow-barrier package, a computer program (Hsieh and Freckleton, 1993) that simulates low-permeability geologic features that impede the horizontal flow of ground water
MODFLOW	Modular finite-difference ground-water flow model developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988) that simulates steady and unsteady flow in a flow system consisting of confined and (or) unconfined layers
MODPATH	A particle-tracking postprocessing package, consisting of two Fortran computer codes, developed by the U.S. Geological Survzey to compute three-dimensional flow paths and times of travel using output from MODFLOW simulations
SBVMWD	San Bernardino Valley Municipal Water District
USGS	U.S. Geological Survey
Water year	The 12-month period that starts October 1 and ends September 30; it is designated by the calendar year in which it ends and which contains 9 of the 12 months

Well- and Spring-Numbering System

Wells and springs are identified and numbered by the State of California according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with "A" in the northeast corner of the section and progressing in a sinusoidal manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The letter "S" inserted before the sequence number indicates a spring. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humboldt (H), Mount Diablo (M), and San Bernardino (S). Because all wells in the study areas of this report are referenced to the San Bernardino base line and meridian, the final letter “S” will be omitted. Well numbers consist of 15 characters and follow the format 001S005W-12L001S. In this report, well numbers are abbreviated and written 1S/5W-12L1. The following diagram of the well-numbering system shows how well number 1S/5W-12L1 is derived.



Numerical Simulation of Ground-Water Flow and Assessment of the Effects of Artificial Recharge in the Rialto–Colton Basin, San Bernardino County, California

By Linda R. Woolfenden *and* Kathryn M. Koczot

ABSTRACT

The Rialto–Colton Basin, in western San Bernardino County, California, was chosen for storage of imported water because of the good quality of native ground water, the known storage capacity for additional ground-water storage in the basin, and the availability of imported water. To supplement native ground-water resources and offset overdraft conditions in the basin during dry periods, artificial-recharge operations during wet periods in the Rialto–Colton Basin were begun in 1982 to store surplus imported water. Local water purveyors recognized that determining the movement and ultimate disposition of the artificially recharged imported water would require a better understanding of the ground-water flow system.

In this study, a finite-difference model was used to simulate ground-water flow in the Rialto–Colton Basin to gain a better understanding of the ground-water flow system and to evaluate the hydraulic effects of artificial recharge of imported water. The ground-water basin was simulated as four horizontal layers representing the river-channel deposits and the upper, middle, and lower water-bearing units. Several flow barriers bordering and internal to the Rialto–Colton Basin influence the direction of ground-water flow. Ground water may flow relatively unrestricted in the shallow parts of the flow system; however, the faults generally become more restrictive at depth. A particle-tracking model was used to simulate advective transport of imported water within the ground-water flow system and to evaluate three artificial-recharge alternatives.

The ground-water flow model was calibrated to transient conditions for 1945–96. Initial conditions for the transient-state simulation were established by using 1945 recharge and discharge rates, and assuming no change in storage in the basin. Average hydrologic conditions for 1945–96 were used for the predictive simulations (1997–2027). Ground-water-level measurements made during 1945 were used for comparison with the initial-conditions simulation to determine if there was a reasonable match, and thus reasonable starting heads, for the transient simulation. The comparison between simulated head and measured water levels indicates that, overall, the simulated heads match measured water levels well; the goodness-of-fit value is 0.99. The largest differences between simulated head and measured water level occurred between Barrier H and the Rialto–Colton Fault. Simulated heads near the Santa Ana River and Warm Creek, and simulated heads northwest of Barrier J, generally are within 30 feet of measured water levels and five are within 20 feet.

Model-simulated heads were compared with measured long-term changes in hydrographs of composite water levels in selected wells, and with measured short-term changes in hydrographs of water levels in multiple-depth observation wells installed for this project. Simulated hydraulic heads generally matched measured water levels in wells northwest of Barrier J (in the northwestern

part of the basin) and in the central part of the basin during 1945–96. In addition, the model adequately simulated water levels in the southeastern part of the basin near the Santa Ana River and Warm Creek and east of an unnamed fault that subparallels the San Jacinto Fault. Simulated heads and measured water levels in the central part of the basin generally are within 10 feet until about 1982–85 when differences become greater. In the northwestern part of the basin southeast of Barrier J, simulated heads were as much as 50 feet higher than measured water levels during 1945–82 but matched measured water levels well after 1982. In the compartment between Barrier H and the Rialto–Colton Fault, simulated heads match well during 1945–82 but are comparatively low during 1982–96. Near the Santa Ana River and Warm Creek, simulated heads generally rose above measured water levels except during 1965–72 when simulated heads compared well with measured water levels.

Average annual total recharge calculated by the model during 1945–96 was about 33,620 acre-feet and average total discharge was about 35,220 acre-feet. Underflow from the Bunker Hill and Lytle Basins accounted for about 59 percent of total recharge. Seepage loss from the Santa Ana River and Warm Creek accounted for about 15 percent of total recharge. Underflow to the Chino and North Riverside Basins accounted for about 65 percent of total discharge. Model results for 1945–96 indicate that the quantity of water removed from storage was about 7,350 acre-feet, and the quantity going into storage was about 5,960 acre-feet, resulting in a net average storage depletion of about 1,390 acre-ft/yr.

A sensitivity analysis was done to determine the model inputs that were most important in affecting model-generated hydraulic heads at the calibration wells. In layers 1, 2, and 3, hydraulic heads were most sensitive to an increase in total recharge. Hydraulic heads in layer 1 also are sensitive to an increase in the streambed conductance. Hydraulic heads in layers 2 and 3 also are sensitive to removal of all internal barrier conditions. In layer 4, hydraulic heads were most sensitive to the removal of all internal barriers and removal of the unnamed fault. Hydraulic heads were least sensitive in layer 1 to a reduction in the primary storage coefficient and the removal of Barrier H; in layer 2, to an increase in the primary storage coefficient and the removal of Barrier H; in layer 3, to a decrease in the primary storage coefficient and an increase in the vertical conductance; and in layer 4 to an increase in the primary storage coefficient and a decrease in the primary storage coefficient.

Predictive simulations were made for three artificial-recharge alternatives, including artificial recharge at Linden Ponds, discontinued artificial recharge, and artificial recharge at Cactus Basin. To extend the ground-water flow model beyond 1996, average hydrologic conditions (natural recharge and discharge) for 1945–96 were used for the predictive simulation period, 1997–2027. Results of the predictive simulations indicate that artificial recharge at Linden Ponds causes water levels to rise northeast of the unnamed fault (which isolates the recharge ponds from the main water-producing part of the basin) but has little influence on water levels southwest of the unnamed fault. The water-level response to artificial recharge at Cactus Basin indicates that wells northwest of Barrier J and northeast of the unnamed fault are sufficiently isolated by the faults to be affected. Water levels southeast of Barrier J and north of the Santa Ana River and Warm Creek rose as much as 50 feet higher than discontinued recharge levels. Water levels near the Santa Ana River and Warm Creek were not affected with artificial recharge at either Linden Ponds or Cactus Basin, indicating that a longer period of recharge would be needed to raise water levels in this area.

Results of the particle-tracking simulations indicate that the imported water would reach production wells only with artificial recharge at Cactus Basin, suggesting that artificial recharge at Cactus Basin may make the imported water more available to production wells than recharge at Linden Ponds. The imported-water particles move only about a mile farther with artificial recharge at Linden Ponds than with discontinued recharge in the basin, indicating that artificial recharge may be only slightly more effective than the absence artificial recharge in the movement of imported water.

INTRODUCTION

The Rialto–Colton Basin, in western San Bernardino County, California, is experiencing continued population growth. Water purveyors rely on ground-water resources to meet local water-supply needs. To supplement native ground-water resources and offset overdraft conditions in the basin during dry periods, artificial-recharge operations during wet periods were begun in 1982 to store surplus imported water originating in the Sierra Nevada; these artificial-recharge operations ended in 1994. Local water purveyors recognized the need to determine the movement and ultimate disposition of the artificially recharged imported water within the Rialto–Colton Basin. It was recognized, also, that this could be accomplished by means of a ground-water flow model of the Rialto–Colton Basin, which could aid in better understanding the ground-water flow system and in evaluating the hydraulic effects of artificial recharge of imported water.

Purpose and Scope

In 1991 the San Bernardino Valley Municipal Water District (SBVMWD) entered into a cooperative program with the U.S. Geological Survey (USGS) to study the ground-water flow system and water chemistry in the Rialto–Colton Basin. In the first phase of the program the geohydrology and water chemistry were described (Woolfenden and Kadhim, 1997). The objectives of the second phase, which are described in this report, were to (1) evaluate and quantify the hydrologic information presented in the first phase of the study, (2) determine the movement and ultimate disposition of artificially recharged imported water, and (3) simulate general long-term effects on water levels likely to occur as a result of using three artificial-recharge alternatives proposed by SBVMWD. The hydrologic analysis in the second phase included the development and calibration of a ground-water flow model, which was used to simulate hydraulic heads in the Rialto–Colton Basin aquifer system. A particle-tracking post processor for the finite-difference flow model was used to simulate the movement and ultimate disposition of the artificially recharged imported water within the Rialto–Colton Basin. The flow model and post processor can provide useful information for evaluating the effectiveness of various artificial-recharge alternatives.

Description of Study Area

The 30-mi^2 Rialto–Colton Basin is a northwest-trending alluvial basin in the upper Santa Ana River drainage area (fig. 1). The basin is about 10 mi long and varies in width from about 3.5 mi in the northwestern part to about 1.5 mi in the southeastern part. It is bounded on the northeast by the San Jacinto Fault, and on the southwest by the Rialto–Colton Fault. The San Gabriel Mountains and the Badlands form the northwestern and southeastern boundaries, respectively. The Santa Ana River cuts across the southeastern part of the basin. Warm and Lytle Creeks join near the southeastern boundary of the basin and then flow to meet the Santa Ana River near the center of the southeastern part of the basin. A canal that diverts water from Warm Creek to North Riverside Basin during 1945–55 (Steve Mains, Western Municipal Water District, oral commun., 1998) intersects Warm Creek within the basin near the San Jacinto Fault and cuts across the southeastern part of the basin in a southerly direction (fig. 2). Several unnamed ephemeral streams drain the San Gabriel Mountains in the northwestern part of the basin.

Historically, irrigated and nonirrigated agriculture were the main land uses in the developed part of the Rialto–Colton Basin. Both agricultural and urban development in the upper Santa Ana River drainage area, including the Rialto–Colton Basin, increased sharply during the 1940's. In 1949, agricultural development, primarily citrus groves and vineyards, covered about half of the basin, and native vegetation covered most of the rest (Marisue Meza, SBVMWD, written commun., 1996). Urban development occupied only a small part of the basin (fig. 3). In 1957, agriculture began to decline. At the same time, urban development began to increase rapidly (California Department of Water Resources, 1970). In 1993, the primary land uses, which covered about two-thirds of the basin, were residential, industrial, and commercial (Marisue Meza, SBVMWD, written commun., 1996) (fig. 4). About one-third of the basin still was undeveloped and covered with native vegetation (shown as "vacant" in fig. 4).

The upper Santa Ana River drainage is characterized by a warm-summer and mild-winter semiarid climate. Rainfall occurs principally from December through April; in summer, occasional thundershowers occur in the adjacent mountains. Mean annual precipitation at San Bernardino for 1871–1998 was 16.45 in.

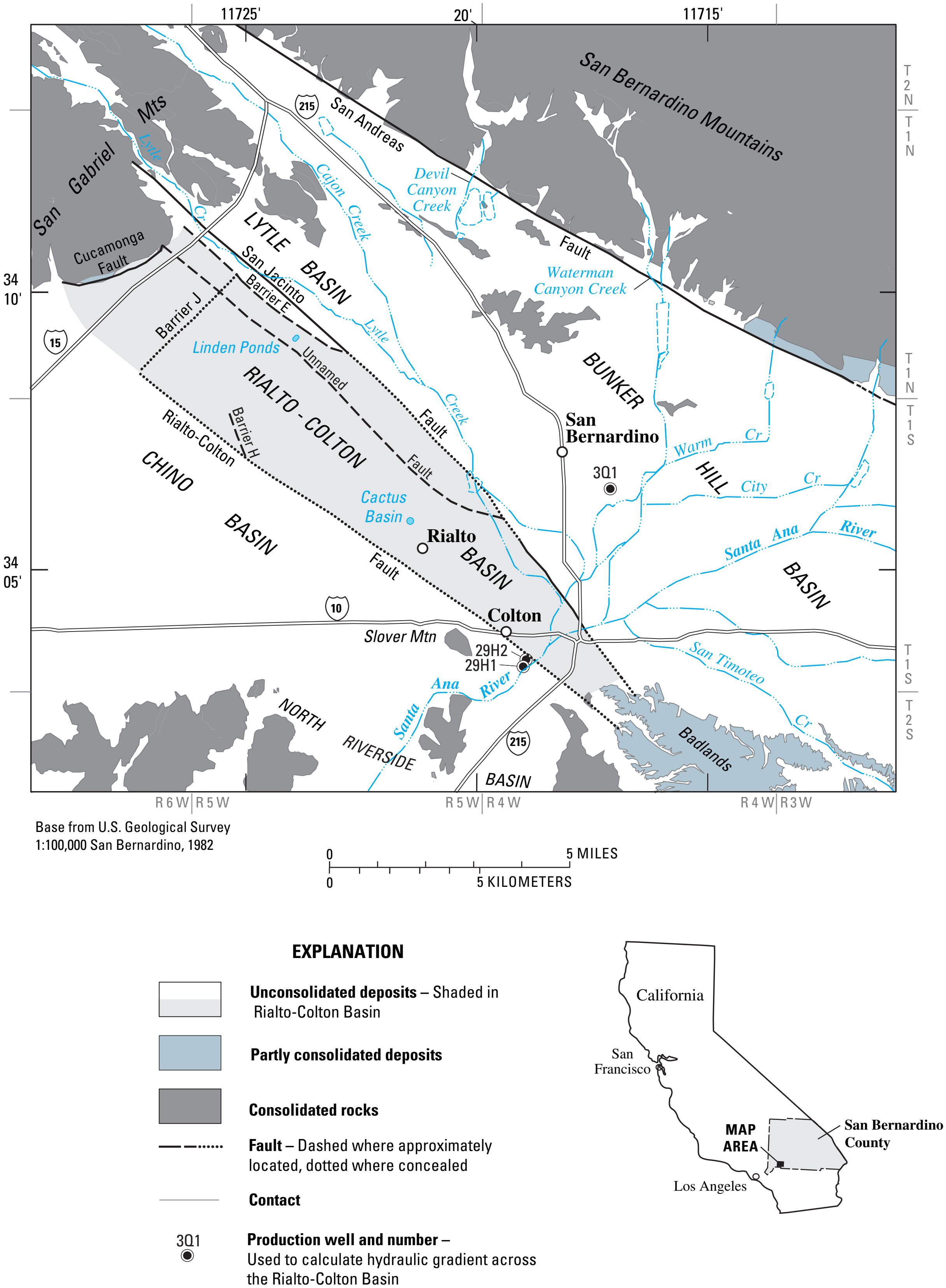


Figure 1. Location and geographic setting of the Rialto–Colton Basin, San Bernardino County, California.

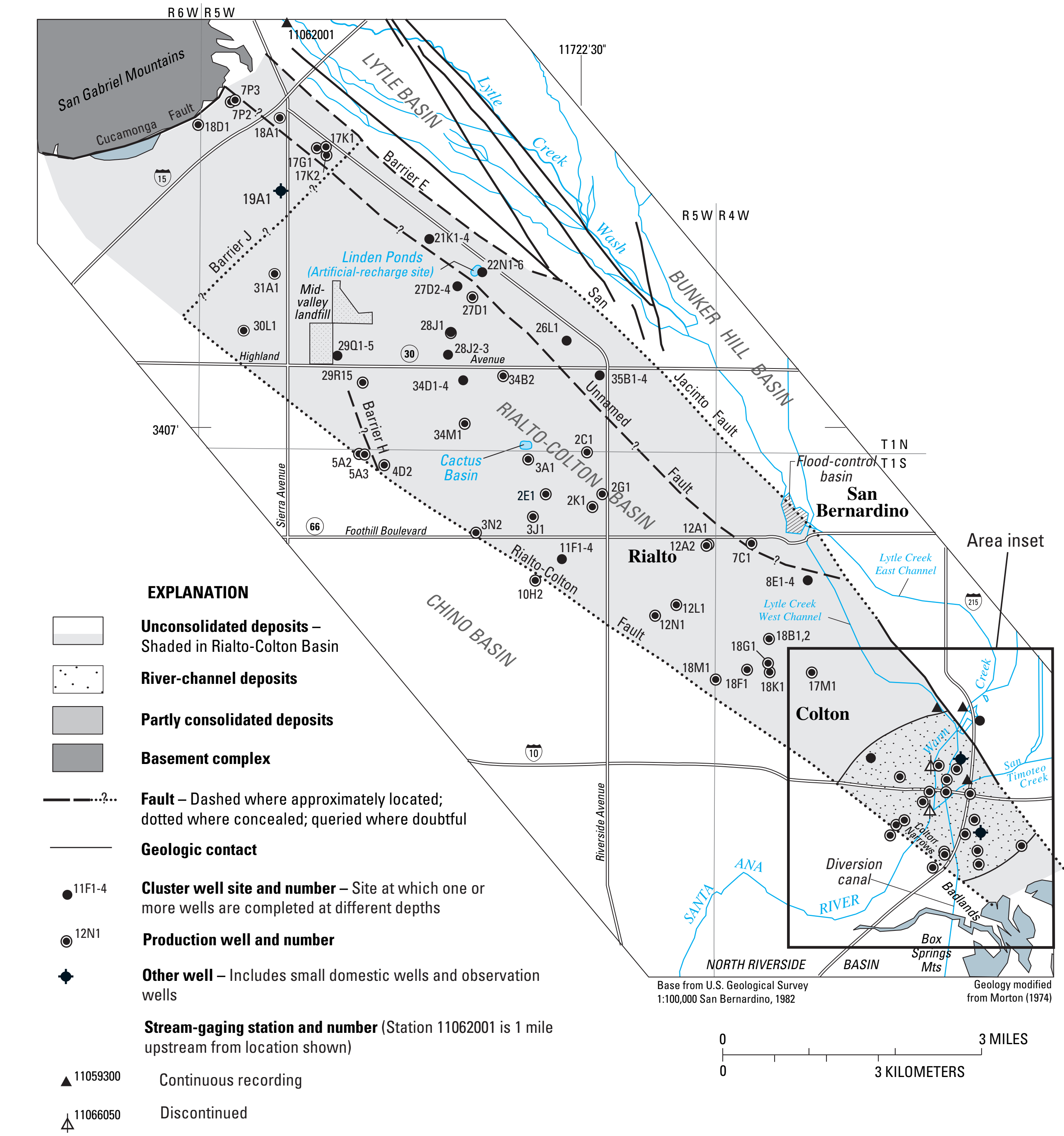


Figure 2. Location of cluster sites, selected production wells, and stream-gaging stations in the Rialto–Colton Basin, San Bernardino County, California.

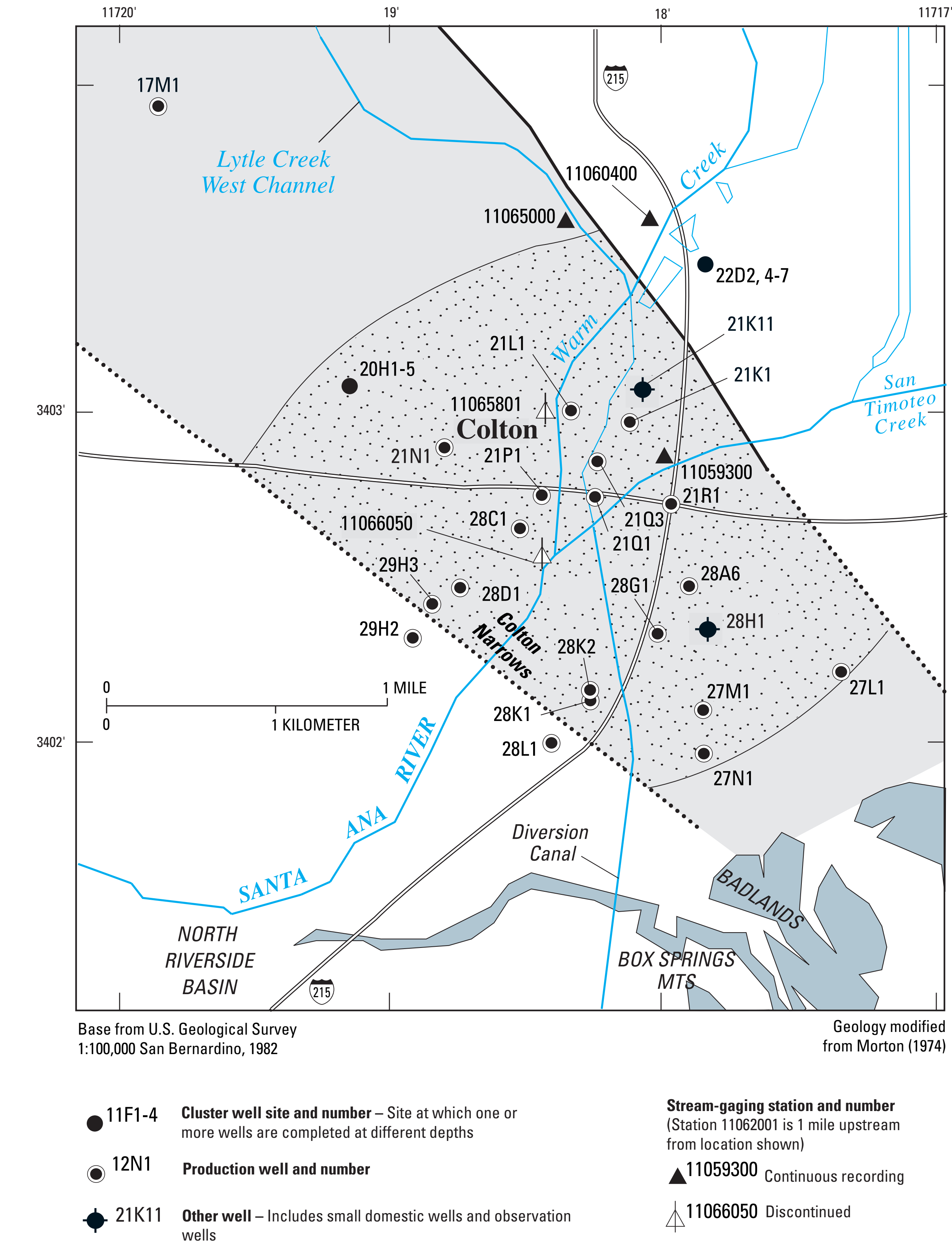


Figure 2.—Continued.

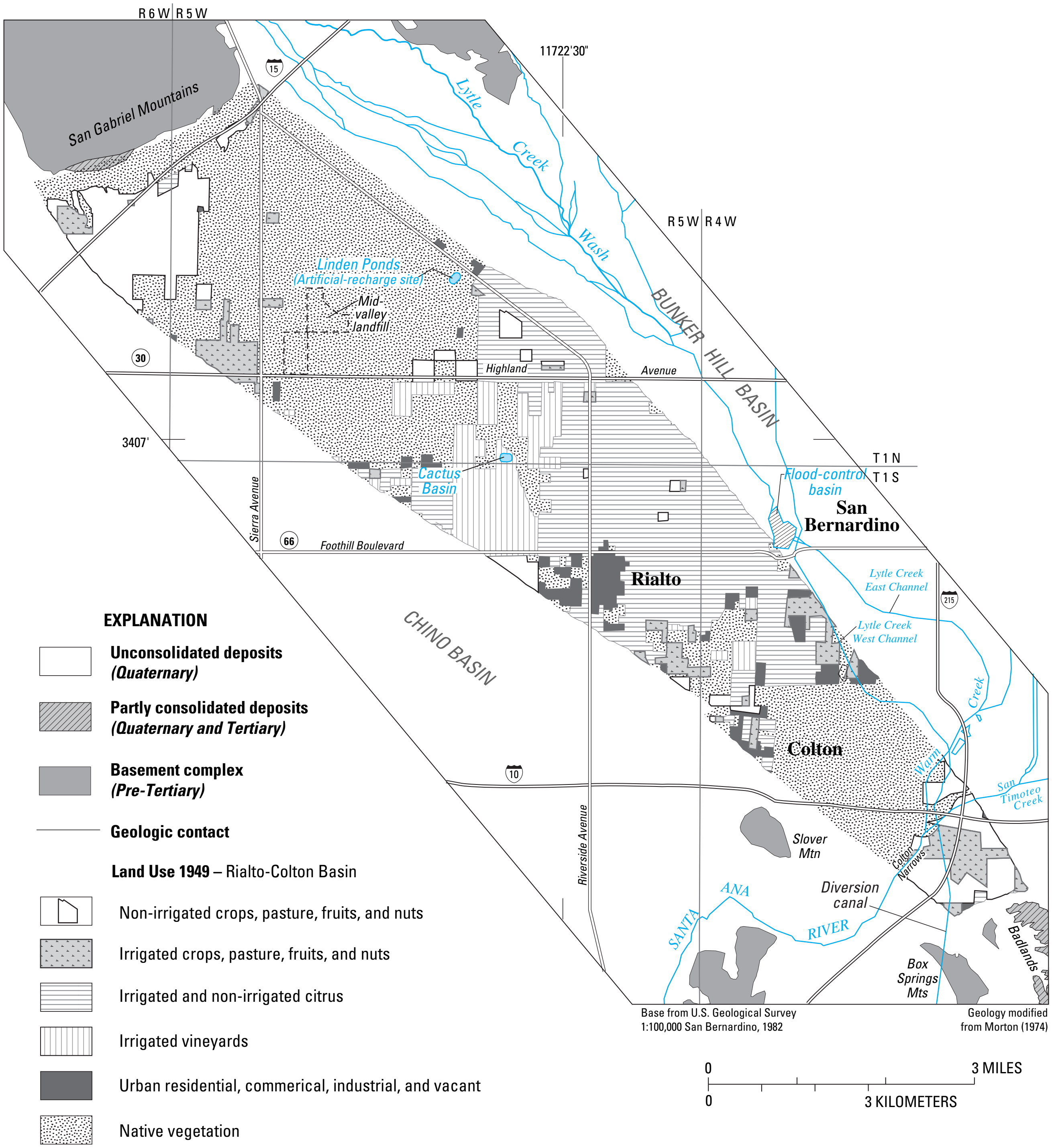


Figure 3. Land use in the Rialto–Colton Basin, San Bernardino County, California, 1949 (from Meza, M., San Bernardino Valley Municipal Water District, written commun., 1996).

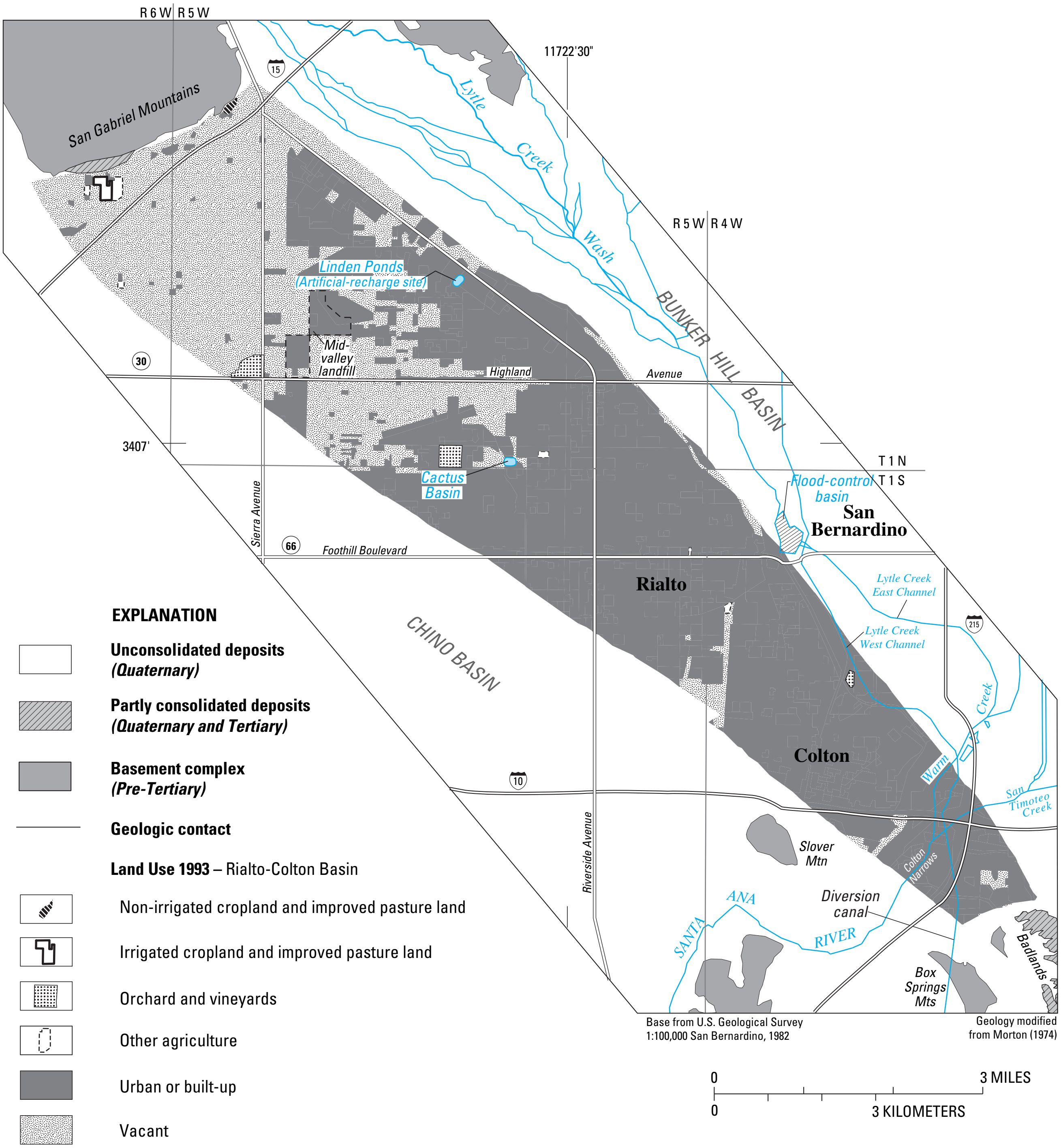


Figure 4. Land use in the Rialto–Colton Basin, San Bernardino County, California, 1993 (from Meza, M., San Bernardino Valley Municipal Water District, written commun., 1996).

(fig. 5). Extremes in precipitation include 37.08 in. in 1884 and 5.46 in. in 1881 (National Oceanic and Atmospheric Administration, 1871–1998). A plot of the cumulative departure from mean annual precipitation (fig. 5) shows wet, dry, and average periods between 1871 and 1998. A positive slope indicates above-average rainfall and a negative slope, below-average rainfall. Major wet periods were 1883–89, 1935–46, and 1977–83. Major dry periods were 1889–1904, 1947–77, and 1984–90. The dry period during 1984–90 was, in part, a reflection of the statewide 6-year drought that occurred during 1987–92.

Field and Analytical Methods

To gain a better understanding of the ground-water system, 11 test holes were drilled in the Rialto–Colton Basin during 1992–94. Eight holes were drilled to depths of 935 to 1,000 ft and three were drilled to depths of 358 to 478 ft. Geophysical logs were obtained for all test holes. Four to six wells were completed at different depths in each of the eight deeper test holes, and one to three wells were completed in each of the three shallower test holes (fig. 2). During 1992–94, water levels in the wells were measured periodically. Beginning in 1996, water levels in 33 wells have been measured by transducers and recorded by data loggers at 15-minute intervals. Manual measurements are made every 4 to 6 weeks when the equipment is serviced. Water levels measured by the transducers are stored in the USGS's Automated Data Processing System (ADAPS) data base; manual measurements are stored in the Ground-Water Site Inventory System (GWSI) data base. Water-level, borehole geophysical, and lithologic data, and analyses of these data, are reported by Woolfenden and Kadhim (1997).

Water was sampled at least twice at all cluster wells (a cluster site contains multiple wells in a borehole that are referred to as "cluster wells") installed for this project during 1992–94, and analyzed for major ions, selected trace elements, nutrients, and the stable isotopes of oxygen and hydrogen (oxygen-18 and deuterium). Selected samples also were analyzed for carbon 13/14 and tritium. During 1992–95, water from selected production wells (fig. 2), a spring in the San Gabriel Mountains, Lytle Creek, and the Santa Ana River was sampled and analyzed for major ions, selected trace elements, nutrients, oxygen-18, and deuterium. Samples from six of the production wells, Lytle Creek, and the Santa Ana River were analyzed for tritium. Water-chemistry data and data analyses for 1992–94 are described by Woolfenden and Kadhim (1997). To complete the water-chemistry data set along a flow path described by Woolfenden and Kadhim (1997), water was sampled from cluster wells 1S/4W-20H4, 1S/4W-20H5, and 1N/5W-21K1-4 for carbon 13/14, and from production well 1N/5W-17K1 for tritium in 1997.

To simulate ground-water flow in the Rialto–Colton Basin, a modular four-layer finite-difference ground-water flow model was constructed using the FORTRAN-based modular computer code MODFLOW developed by the USGS (McDonald and Harbaugh, 1988). In this code, a governing partial differential equation for ground-water flow is approximated by finite-difference equations that are solved over a network composed of rectangular blocks (or cells) representing the area modeled. Solutions to the differential equations or the difference equations are hydraulic heads in the various model blocks at specific times. Major options required for simulation and for solution in the numerical model are referred to as "packages" (McDonald and Harbaugh, 1988, p. 3–20) and, for this study, include the Basic (input and output procedures), Block-Centered Flow, Well, Recharge, Evapotranspiration, and General-Head-Boundary packages. The preconditioned conjugate gradient (PCG2) solver was used for the initial-conditions simulation, and the Strongly Implicit Procedure solver was used for the transient simulation. The convergence criterion used for both solvers was 0.001 ft. Additional packages (not included by McDonald and Harbaugh, 1988) are the Horizontal-Flow Barrier Package (Hsieh and Freckleton, 1993), which is used to simulate faults that form boundaries between components of the flow system, and the streamflow-routing package (Prudic, 1989), which is used to model the interaction of the Santa Ana River and Warm Creek with the ground-water flow system. The stream-routing package is not a true surface-water flow model but rather is an accounting program that tracks the flow in one or more streams that interact with the ground water (Prudic, 1989).

The computer model used in this study to simulate advective transport of imported water through the ground-water flow system is MODPATH (Pollock, 1994). MODPATH employs a particle-tracking technique to compute pathlines based on the results of MODFLOW. A complete description of MODPATH's

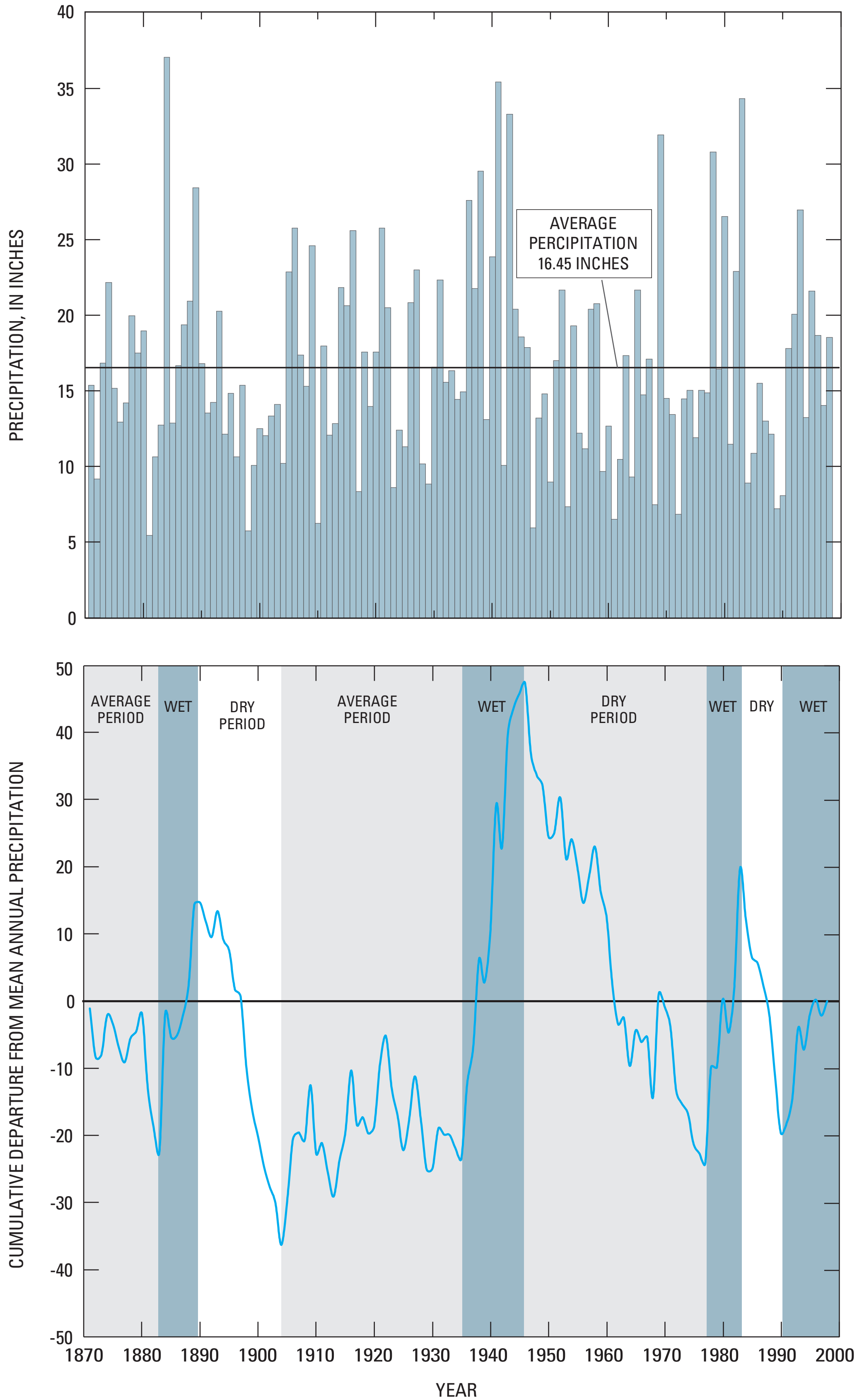


Figure 5. Annual precipitation and cumulative departure from mean annual precipitation at San Bernardino, California, 1871–1998.

theoretical development, solution techniques, and limitations is given by Pollock (1994).

Acknowledgments

Special acknowledgment is given to the staff at San Bernardino Valley Municipal Water District— especially Louis Fletcher, Bob Reiter, Randy Van Gelder, and Sam Fuller—for their continued support for this program. Also acknowledged are Steve Mains from Western Municipal Water Agency for providing updated pumpage data. Babs Makinde-Odusola from the city of Riverside; Anthony Araiza and Manju Book from West San Bernardino County Water District; and Gene McMeans from Riverside-Highland Water Company are acknowledged for providing water-level data.

GEOHYDROLOGY

The geohydrology of the Rialto–Colton Basin is discussed in detail by Dutcher and Garrett (1963) and Woolfenden and Kadhim (1997). The geohydrologic analysis presented in these reports is summarized here to provide the necessary background information for the reader to understand the construction of the numerical model discussed in the following sections. For a more complete description of the geohydrology of the Rialto–Colton Basin, the reader is referred to these reports.

Stratigraphic Units

Stratigraphic units in the Rialto–Colton Basin are divided into four general categories: unconsolidated Quaternary alluvial deposits (Holocene and Pleistocene); partly consolidated Quaternary to Tertiary continental deposits (early Pleistocene to late Pleistocene); consolidated Tertiary continental deposits [Pliocene (?)]; and pre-Tertiary basement complex (Dutcher and Garrett, 1963). The unconsolidated alluvial deposits are composed of dune sand, river-channel deposits, and younger and older alluvium. The partly consolidated continental deposits underlie the alluvial deposits as lenticular bodies and crop out in the Badlands where they form the southeastern boundary of the Rialto–Colton Basin. These deposits also crop out at the base of the San Gabriel Mountains, which form the northwestern boundary of the basin. The consolidated continental deposits underlie the partly consolidated or alluvial deposits. The basement complex underlies the alluvial and continental deposits, and crops out in the San Gabriel Mountains (Dutcher and Garrett, 1963). The consolidated continental deposits and basement complex are considered non-water bearing and, therefore, are not part of the ground-water system.

Description of Aquifer System

Because the stratigraphic units do not form well-defined aquifers and confining beds, the ground-water system was divided into water-bearing units. The division of the ground-water system into water-bearing units is based predominantly on analysis of lithology from drill cuttings and borehole geophysical logs. Analysis of these data is discussed in detail by Woolfenden and Kadhim (1997). The water-bearing units include the river-channel deposits, and the upper, middle, and lower water-bearing units. These water-bearing units may include more than one stratigraphic unit. Lithologic logs indicate that subsurface materials are largely heterogeneous alluvium that consists of various thicknesses of interbedded gravel, sand, silt, and clay. The resistivity logs indicate that the resistivity generally decreases with increasing depth. The river-channel deposits were penetrated at only one site (1S/4W-20H1-5) completed during Phase 1 of this study. Although the lithology of the river-channel deposits at this site is similar to that of the upper water-bearing units, the resistivity log abruptly shifts to the left (indicating less resistive materials) at the contact between the two units (Woolfenden and Kadhim, 1997, p. 17). The materials composing the upper water-bearing unit are more resistive (curve shifts to the right) than those of the middle water-bearing unit (interbedded sand and clay). The materials composing the lower water-bearing unit (interbedded fine sand, silt, and clay) are less resistive (curve shifts to the left) than those composing the middle water-bearing unit (Woolfenden and Kadhim, 1997).

The water-bearing units are unconfined to partly confined and are in hydraulic connection with each other. Consolidated deposits underlying the lower water-bearing unit form the base of the ground-water system. The geohydrologic sections of Woolfenden and Kadhim (1997) were updated and modified on the basis of these data and model calibration (described in the

“Transient Simulation” section) for this report. The changes include a decrease in the bottom altitude of layer 3 in the vicinity of Barrier J and extension of the unnamed fault. The lines of geohydrologic section are shown in figure 6, and the geohydrologic sections, including resistivity logs, are shown in figure 7.

Water-Bearing Units

The river-channel deposits (fig. 6) underlie the present channels of Warm Creek and the Santa Ana River in the southeastern part of the basin. The northwestern boundary of the river-channel deposits trends from east to west across the Rialto–Colton Basin north of cluster site 1S/4W-20H1-5. The southeastern boundary trends from east to west south of production well 1S/4W-27M1 (fig. 7, sections *A–A′* and *B–B′*). These deposits consist of coarse sand and gravel interbedded with lower permeability deposits of fine sand and clay. Thickness of the river-channel deposits ranges from a feather edge to about 200 ft (fig. 4, sections *A–A′*, *B–B′*, and *F–F′*.

The upper water-bearing unit is present throughout the Rialto–Colton Basin (fig. 7, all sections). This unit consists of alluvial-fan deposits that grade to older river-channel deposits near the Santa Ana River and Warm Creek. The upper water-bearing unit underlies the river-channel deposits near the Santa Ana River and Warm Creek, and it is the uppermost unit throughout the rest of the basin. The alluvial fan deposits consist of coarse sand and gravel, cobbles, and boulders. The older river-channel deposits generally are finer grained than are the alluvial fan deposits. The upper water-bearing unit ranges in thickness from a feather edge in the northwestern part of the basin (fig. 7, sections *A–A′* and *B–B′*) to about 300 ft (fig. 7, all sections). The upper water-bearing unit was unsaturated in the northwestern part of the basin during 1945–96 and was saturated in the southeastern part from the vicinity of production wells 1S/4W-18G1, 1S/4W-18F1, and 1S/4W-18B2 to the southeastern basin boundary during the same period (fig. 2).

The middle water-bearing unit exists throughout the basin and consists primarily of coarse to medium sand and interbedded fine sand and clay. The clay beds are more extensive in the northwestern part of the basin near the Rialto–Colton Fault. The middle water-bearing unit ranges in thickness from about 240 to 600 ft and is thickest in the northwestern part of the basin southeast of Barrier J (fig. 7, all sections). The middle water-bearing unit is the main source of water to wells in the Rialto–Colton Basin (Woolfenden and Kadhim, 1997).

The lower water-bearing unit exists throughout the basin southeast of Barrier J and consists mainly of interbedded sand and clay. The thickness of this unit ranges from about 100 ft in the southeastern part of the basin to about 400 ft in the other parts of the basin (fig. 7, all sections).

Horizontal-Flow Barriers

Barrier E, the San Jacinto Fault, the Rialto–Colton Fault, Barrier J, Barrier H, and an unnamed fault that subparallels the San Jacinto Fault about 1 mi to the southwest act as partial barriers to ground-water flow. Ground water may flow relatively unrestricted in the shallow parts of the flow system; however, the faults generally become more restrictive at depth. Barrier E forms the northeastern boundary of the Rialto–Colton Basin, separating it from the Lytle Basin (fig. 2). Ground water flows across the section of Barrier E between Barrier J and the San Gabriel Mountains north of Barrier J, and to the junction of Barrier E and the San Jacinto Fault south of Barrier J.

The San Jacinto Fault forms the northeastern boundary of the Rialto–Colton Basin south of its junction with Barrier E, separating it from the Bunker Hill Basin (fig. 2). Ground water flows from the Bunker Hill Basin across the San Jacinto Fault in the vicinity of Warm Creek and the Santa Ana River in the river-channel deposits and upper water-bearing unit.

The Rialto–Colton Fault forms the southwestern boundary, separating the basin from the Chino and North Riverside Basins (fig. 2). Ground water flows across the Rialto–Colton Fault in the southeastern part of the basin in the river-channel deposits and in the upper and middle water-bearing units, as discussed in the “Boundary Conditions” section of this report.

Barriers J and H were described by Dutcher and Garrett (1963); the extension of the unnamed fault north of Barrier J was described by Geosciences Support Services, Inc. (1992) and is referred to as “Barrier P1”; and the unnamed fault south of Barrier J was first described by Woolfenden (1994) and an updated description is given by Woolfenden and Kadhim (1997). The location and the extent of Barrier H and the unnamed fault were modified during model calibration as described later in the “Model Calibration” section. The unnamed fault was connected to “Barrier P1” for

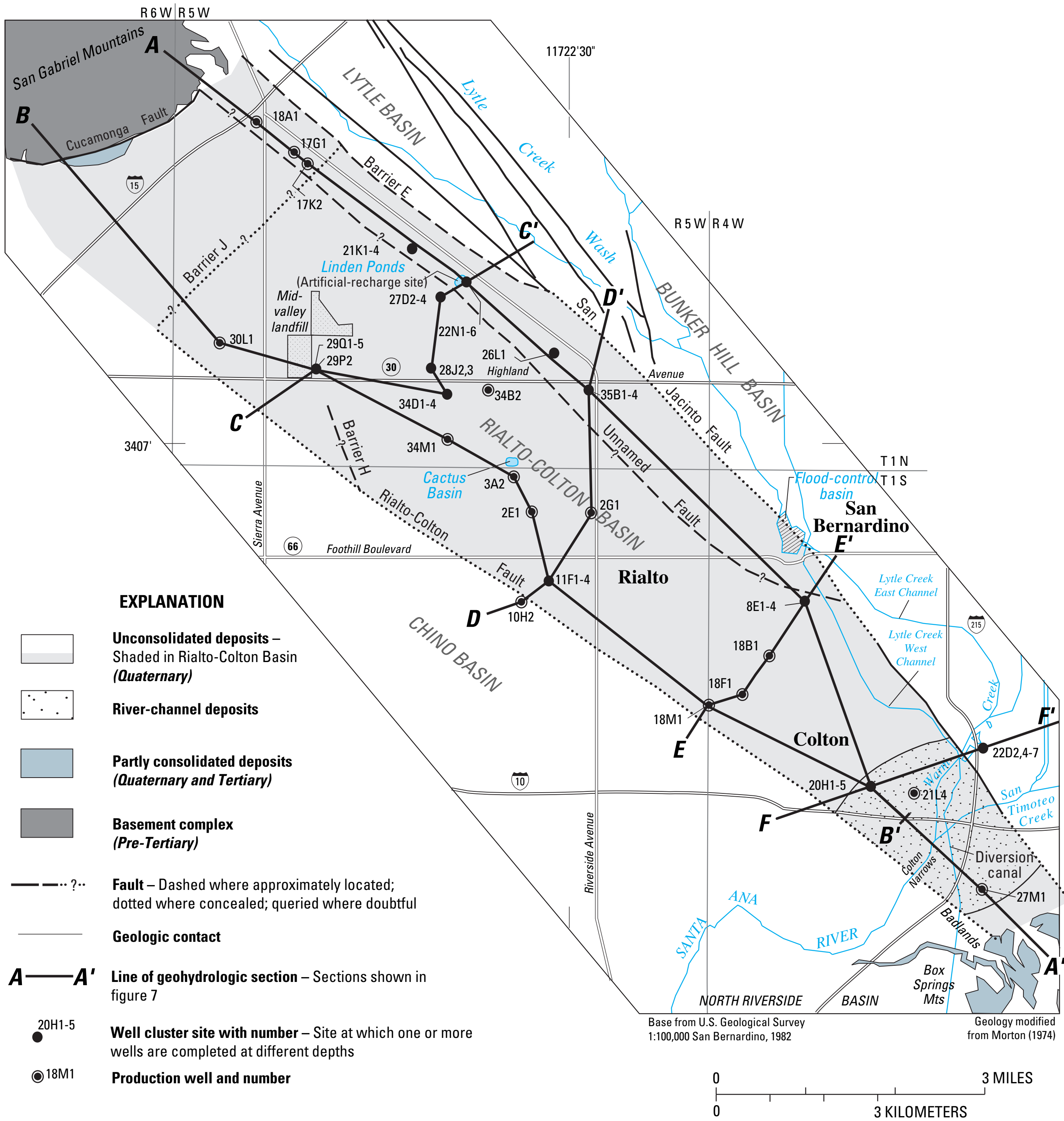


Figure 6. Location of cluster sites, selected production wells, and lines of geohydrologic section in the Rialto–Colton Basin, San Bernardino County, California.

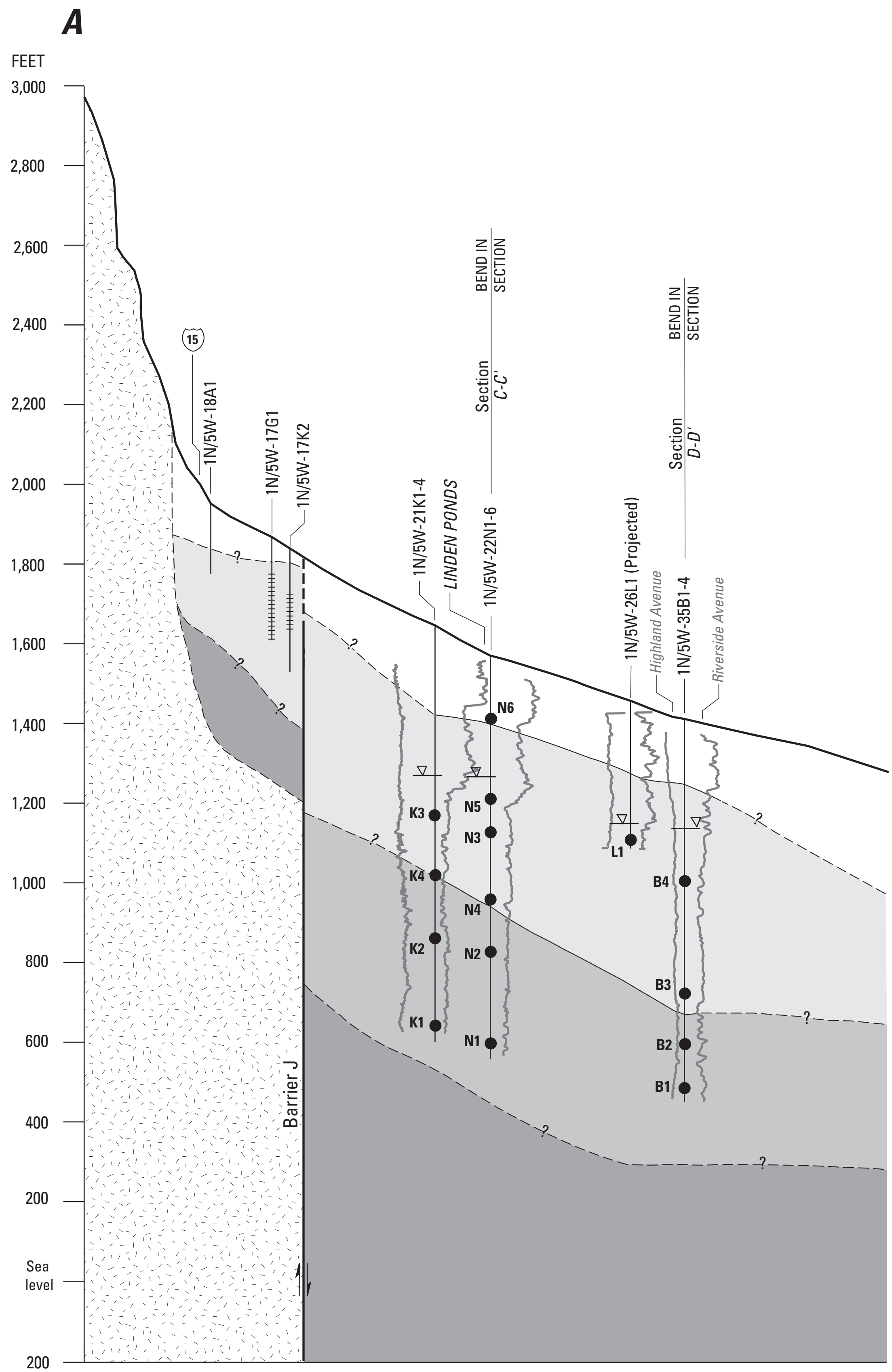
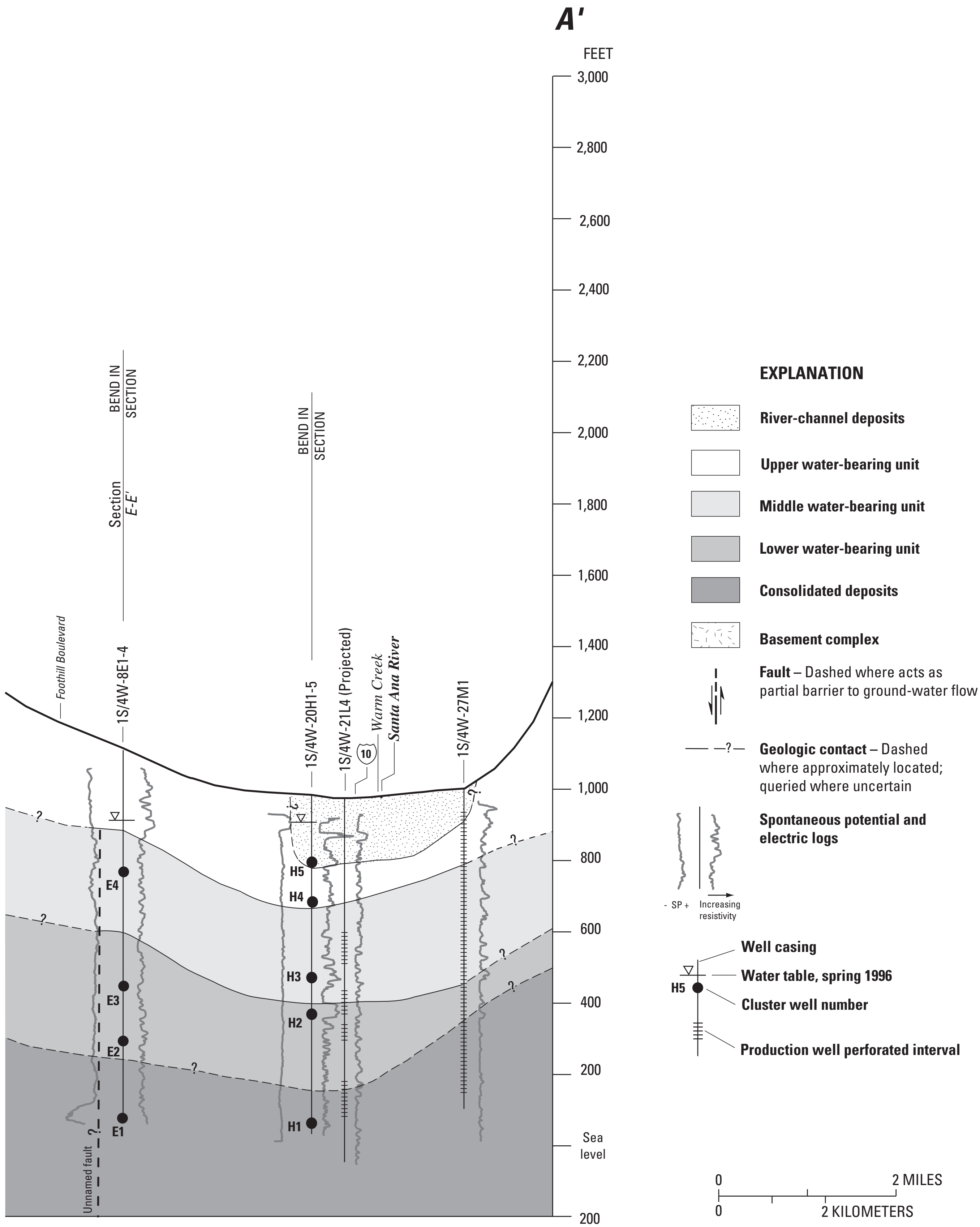


Figure 7. Generalized geohydrologic sections *A–A′* through *F–F′* in the Rialto–Colton Basin, San Bernardino County, California.



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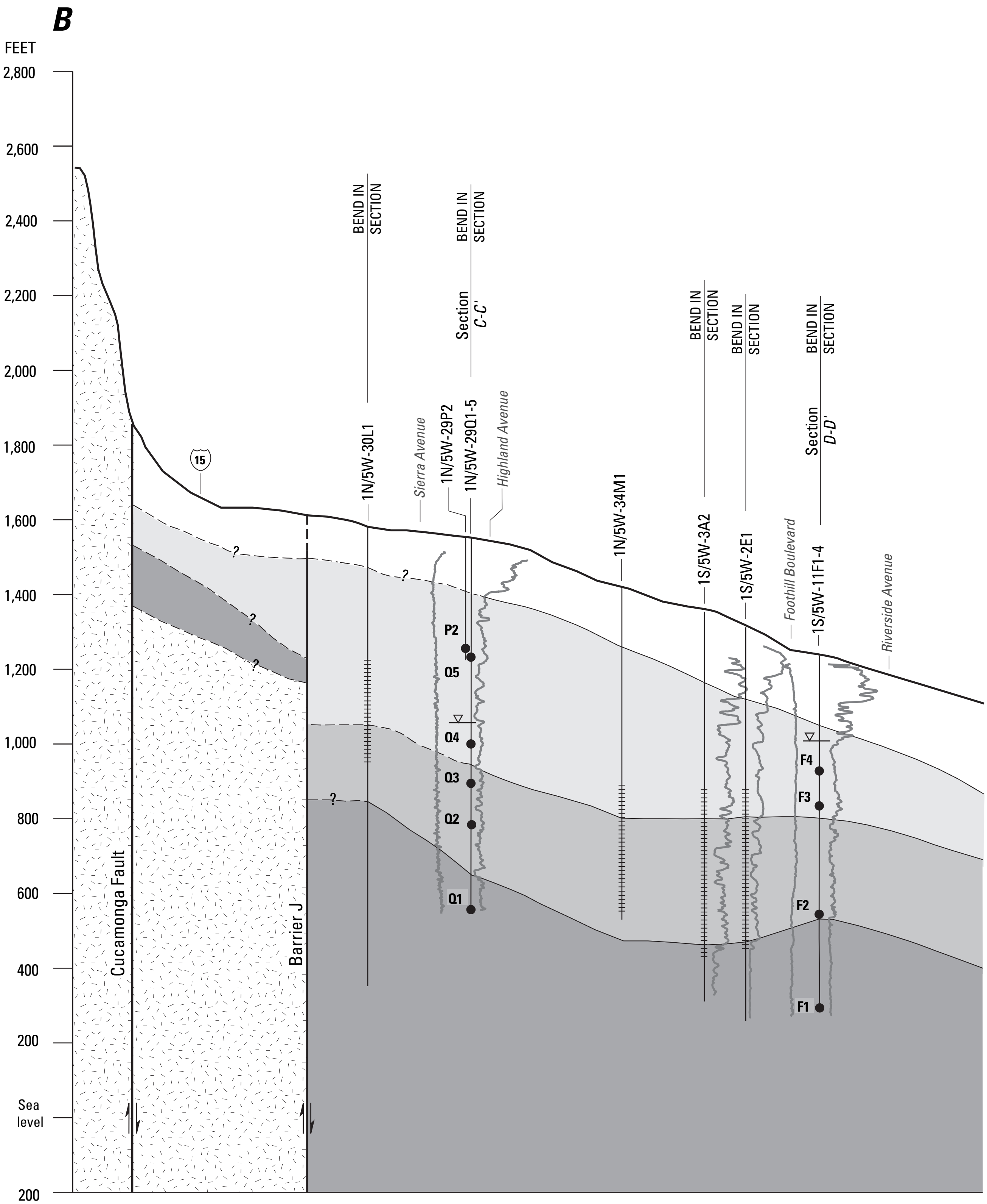

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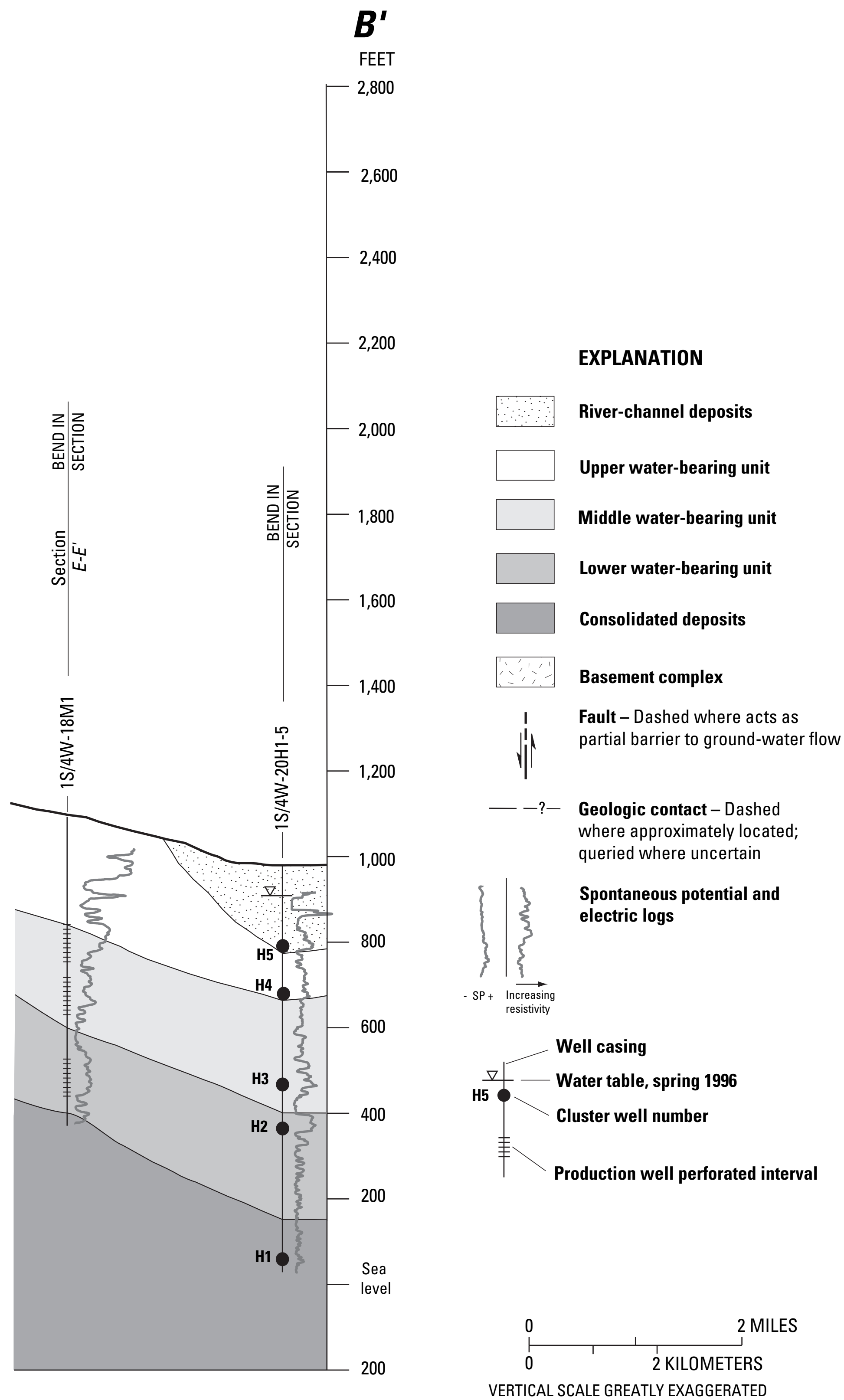
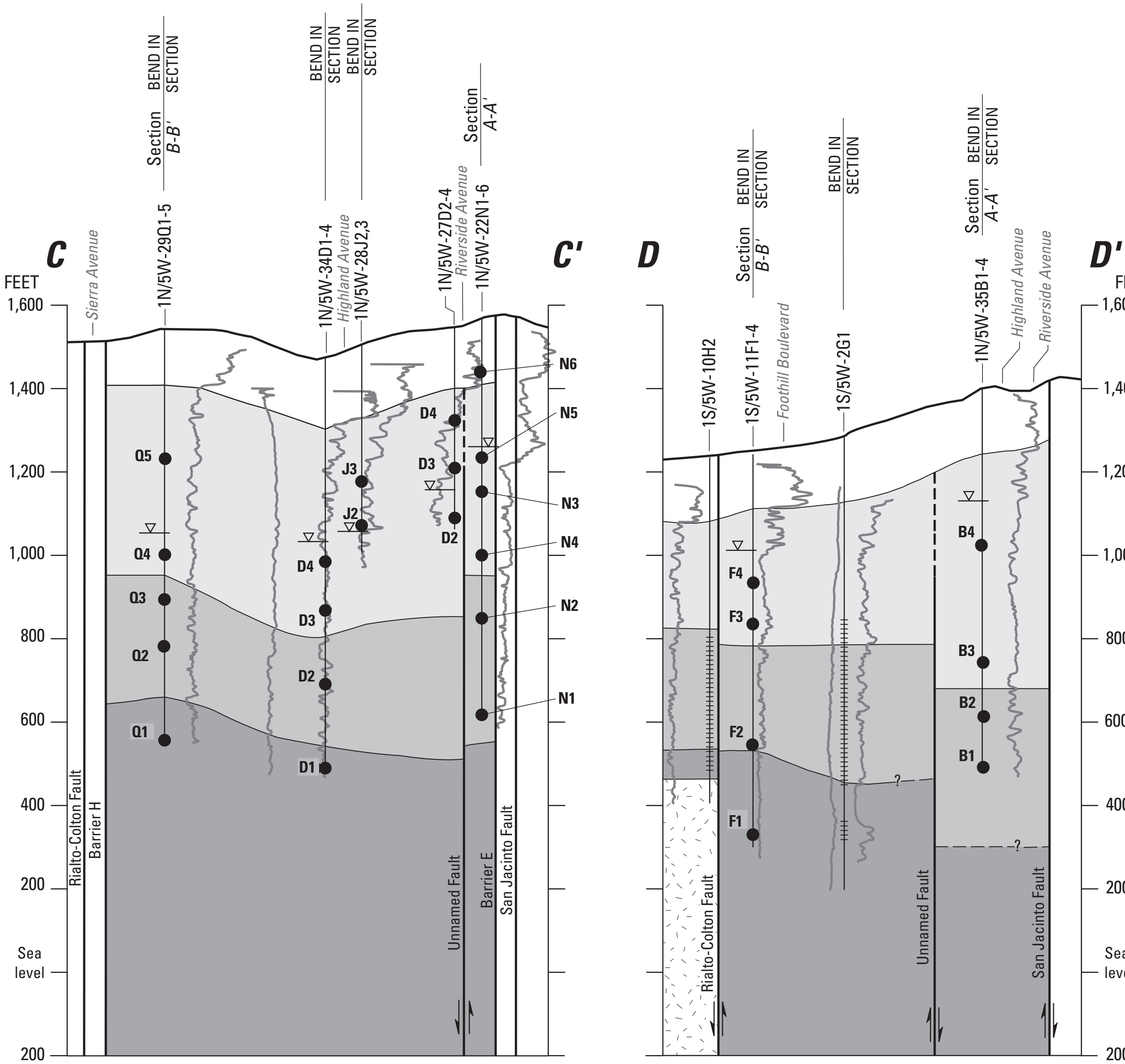


Figure 7.—Continued.

this report. These faults and barriers impede ground-water movement; however, ground water may flow relatively unrestricted above these faults and barriers in unfaulted parts of the alluvium, and to varying degrees across the vertical planes of these faults and barriers throughout their lengths.

Ground-Water Levels and Movement

Composite potentiometric contours for spring 1945 that were constructed by Dutcher and Garrett (1963) were modified for this report (fig. 8). Water levels were measured in production wells that were perforated in more than one water-bearing unit and, therefore, represent composite water levels. Potentiometric contour lines modified (redrawn at a different scale) from Dutcher and Garrett (1963) show that ground water moved southward on the north side of Barrier J.



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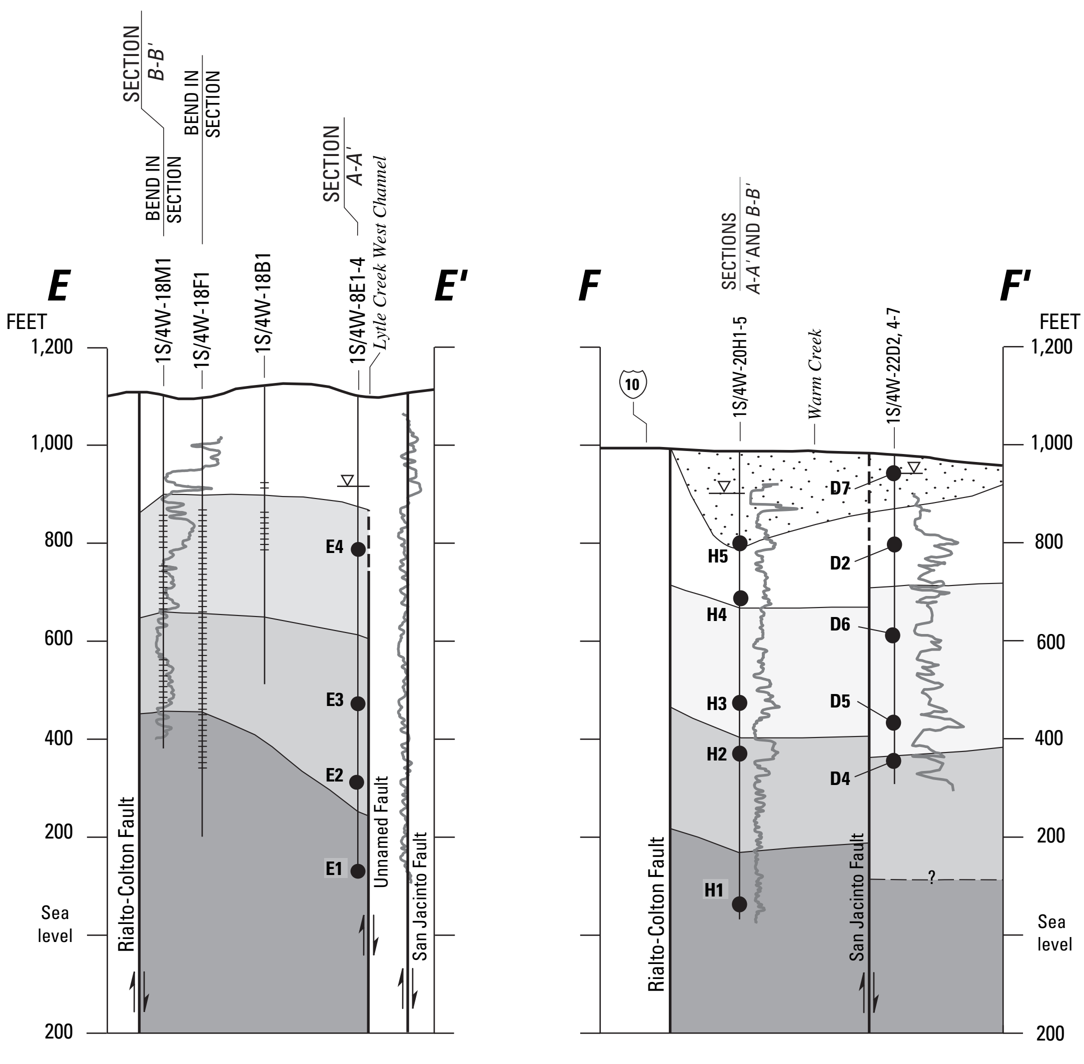
The potentiometric contours show that ground water moved southeastward from Barrier J between the San Jacinto Fault and the Rialto–Colton Fault, and westward and southwestward from the San Jacinto Fault near the Santa Ana River and Warm Creek. Data for 1945 were not available east of the unnamed fault, and contour lines were not drawn in that area.

Ground-water levels in the Rialto–Colton Basin during 1992–98 were determined from measurements of static water levels in 37 cluster wells at 11 sites. Water-level measurements made during Phase 1 of this study (1992–95) indicate that ground-water movement in the river-channel deposits and the upper water-bearing unit generally was from northeast to southwest in the southeastern part of the basin in 1993 (Woolfenden and Kadhim, 1997). Ground water flows across the San Jacinto Fault from the Bunker Hill Basin to the Rialto–Colton Basin, and across the Rialto–Colton Fault from the Rialto–Colton Basin to the Chino and North Riverside Basins (Woolfenden and Kadhim, 1997).

Ground-water movement in the middle water-bearing unit in spring 1996 generally was from northwest to southeast (fig. 9*A*). The potentiometric contour lines south of Barrier J and west of the unnamed fault for this period are similar to those drawn by Woolfenden and Kadhim (1997) for spring 1994, indicating that the direction of ground-water movement did not change significantly between 1994 and 1996. Potentiometric contours east of the unnamed fault for



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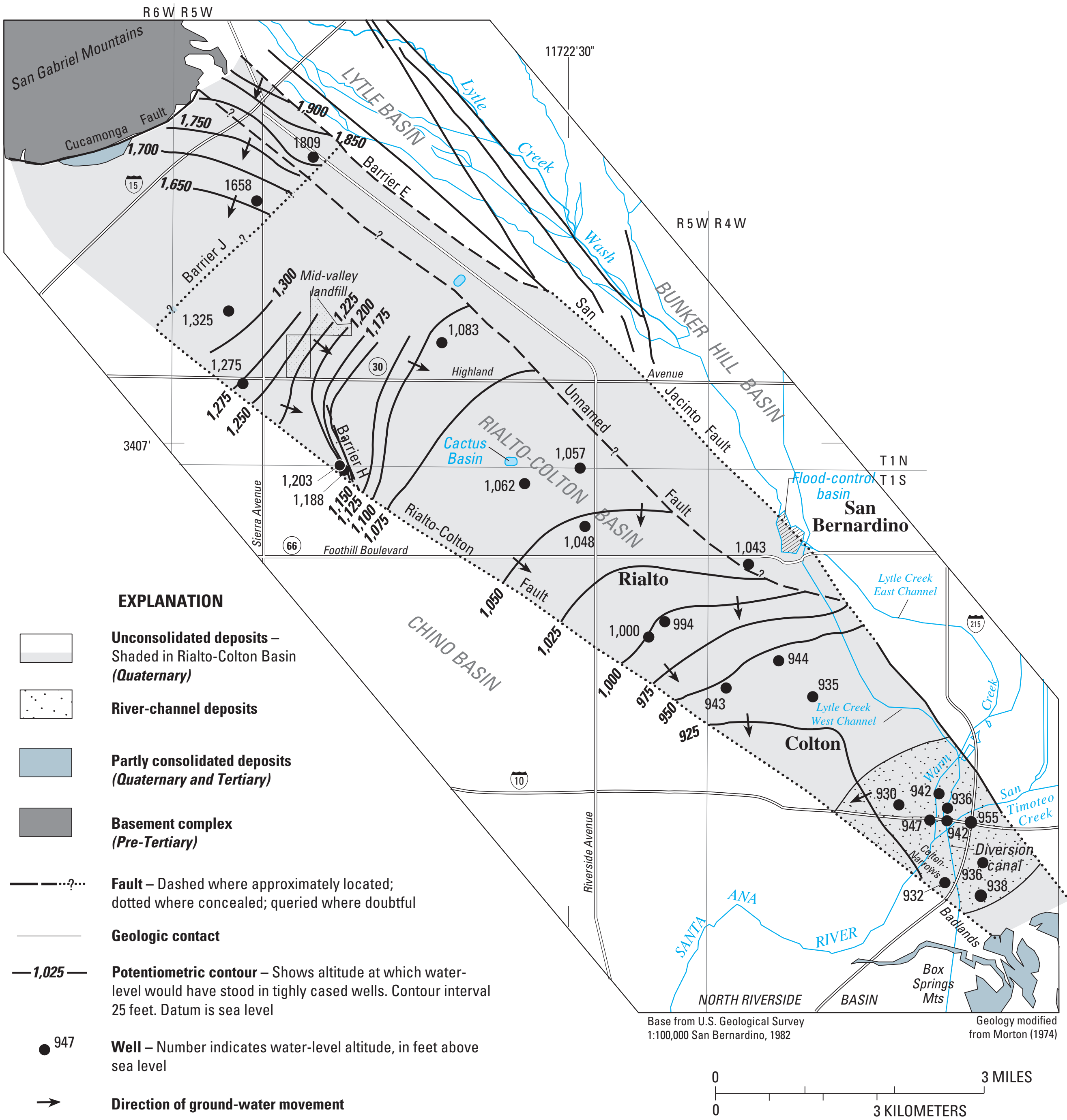


Figure 8. Composite potentiometric contours and direction of ground-water movement, spring 1945, in the Rialto–Colton Basin, San Bernardino County, California (modified from Dutcher and Garrett, 1963).

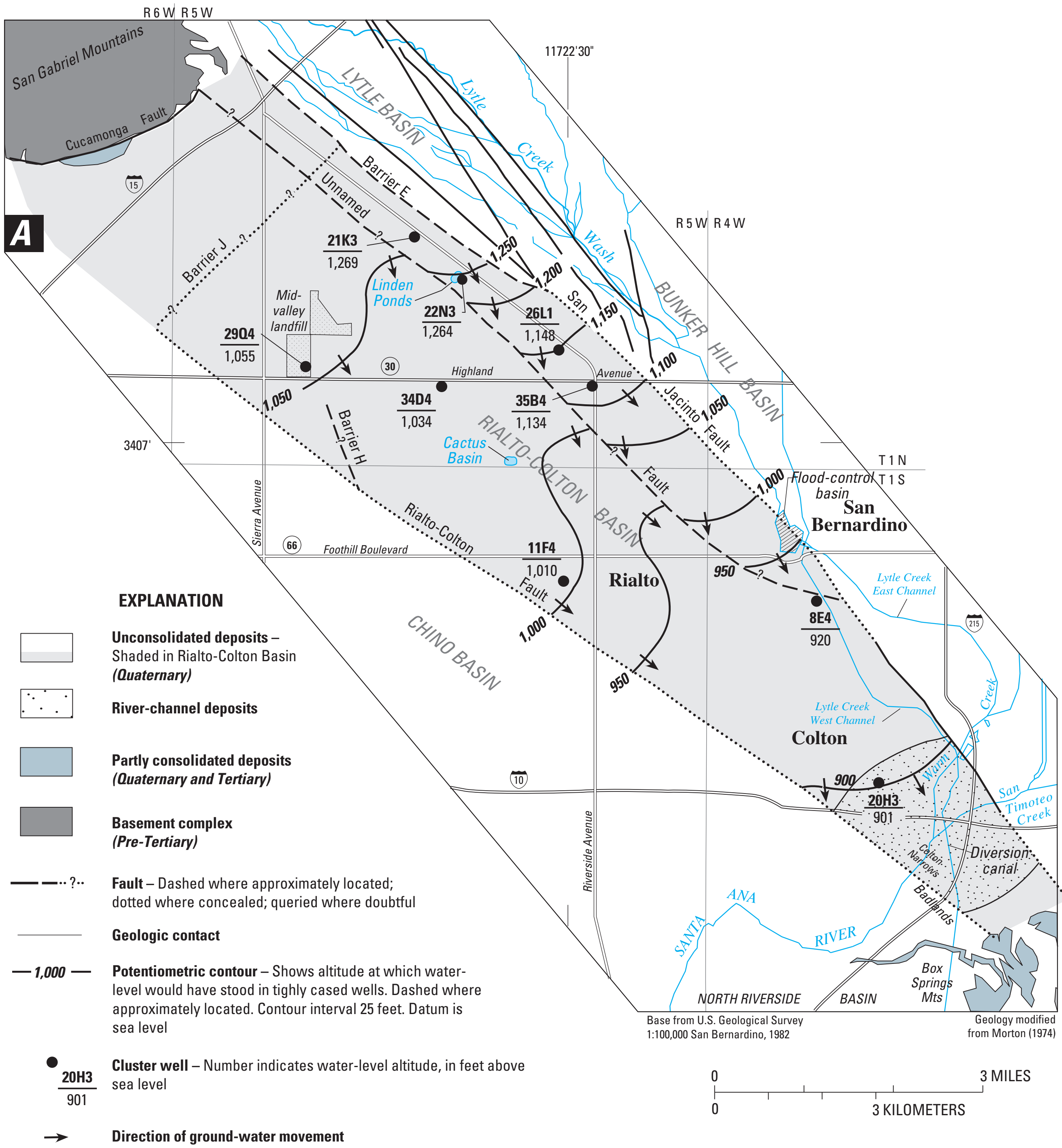


Figure 9. Potentiometric contours and direction of ground-water movement in the middle water-bearing unit (***A***), and in the lower water-bearing unit ***(B)***, spring 1996, in the Rialto–Colton Basin, San Bernardino County, California.

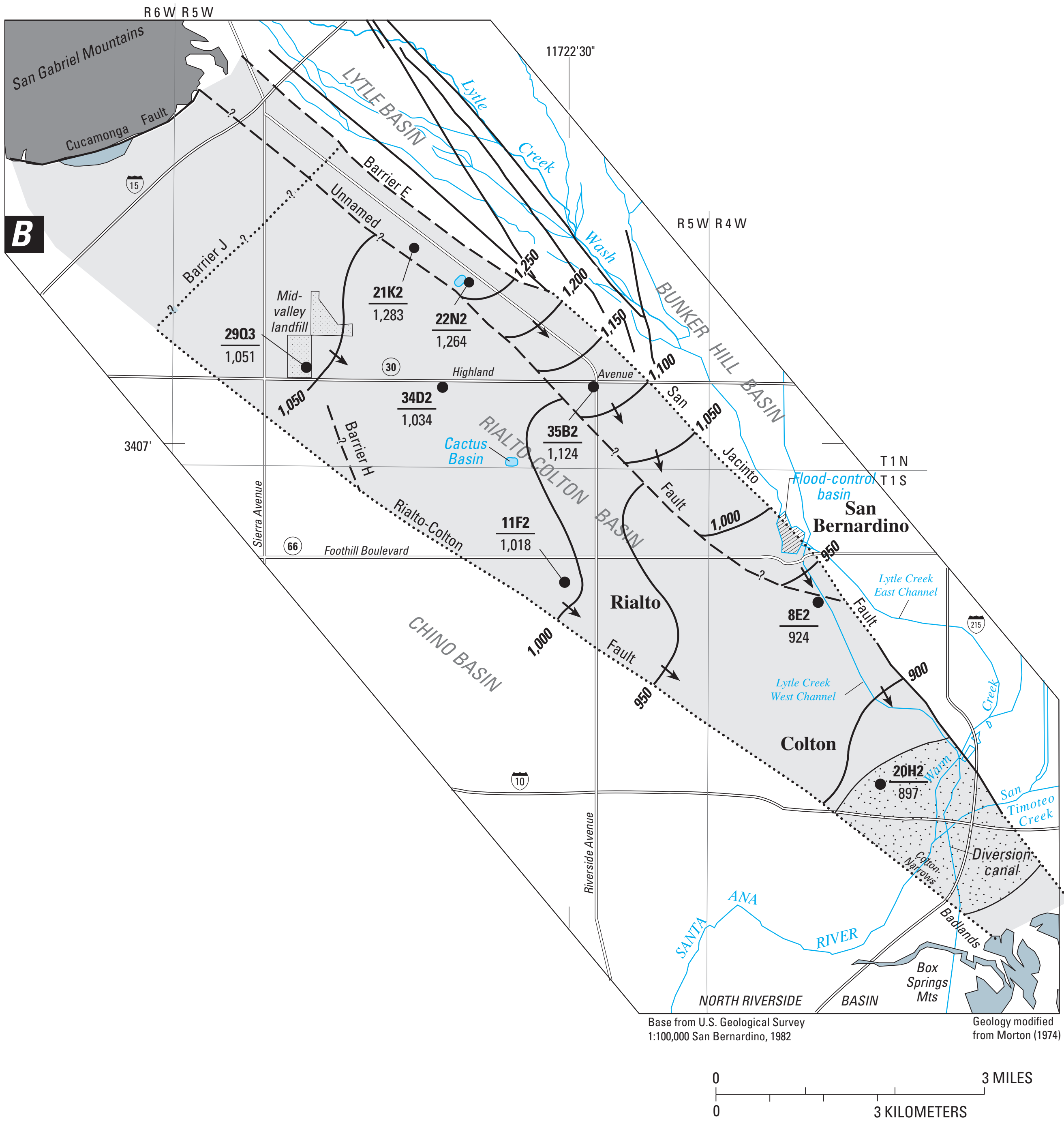


Figure 9.—Continued.

1996 indicate greater movement (steeper gradient) of water across the fault than in 1994. Ground-water levels declined as much as 24 ft northeast of the unnamed fault and rose as much as 8 ft in the northwestern part of the basin. Geosciences Support Services, Inc. (1992), showed that ground water moved from the fractured and weathered basement complex in the San Gabriel Mountains and southwestward across Barrier E from the Lytle Basin to the Rialto–Colton Basin north of Barrier J. Although Barrier J impedes ground-water flow in the northwestern part of the basin, ground water can flow over the top of the barrier in the unfaulted part of the alluvium or where the fault is a less restrictive barrier. Once across Barrier J, ground water in the middle water-bearing unit moves southeastward. The unnamed fault, which subparallels the San Jacinto Fault, acts as a partial barrier and constrains ground-water movement to a narrow corridor between the two faults.

Ground water in the lower water-bearing unit also moves from the northwest to the southeast (fig. 9B) along the long axis of the basin. The unnamed fault acts as a highly restrictive barrier to ground-water flow in this unit (Woolfenden and Kadhim, 1997).

Long-term (1928–98) water levels in four production wells (fig. 2) are shown in figure 10. Well 1N/5W-17K1 (fig. 2) is located northwest of Barrier J in a recharge area (underflow from Lytle Basin); well 1S/5W-3A1 (fig. 2) is in the central part of the basin and is a key well mentioned in a 1969 Superior Court judgement requiring that water levels be maintained at specified levels (S. Fuller, SBVMWD, oral commun., 1992); well 1S/5W-12L1 is in the southwestern part of the basin and also is a key well; and well 1S/4W-21N1 is in the south-central part of the basin near the Santa Ana River and Warm Creek (fig. 2). Wells 1N5W-17K1 and 1S/5W-12L1 are perforated exclusively in the middle water-bearing unit; well 1S/5W-3A1 is perforated in the middle and lower water-bearing units; and well 1S/4W-21N1 is perforated in all water-bearing units (Woolfenden and Kadhim, 1997).

Ground-water levels declined almost continuously in wells 1S/5W-12L1, 1S/5W-3A1, and 1S/4W-21N1 (fig. 10) during most of a dry period during 1947–77 (fig. 5). Water levels began to recover before the end of the dry period probably owing to above-average precipitation in 1969 (fig. 5) and a reduction in pumpage. Water levels in well 1S/4W-21N1 responded quickly to changes in precipitation (figs. 5 and 10) because of the well's proximity to Warm Creek and the Santa Ana River. Water levels in well 1N/5W-17K1 did not respond to pumpage and recharge stresses on the ground-water system in the same manner as did wells southeast of Barrier J (fig.

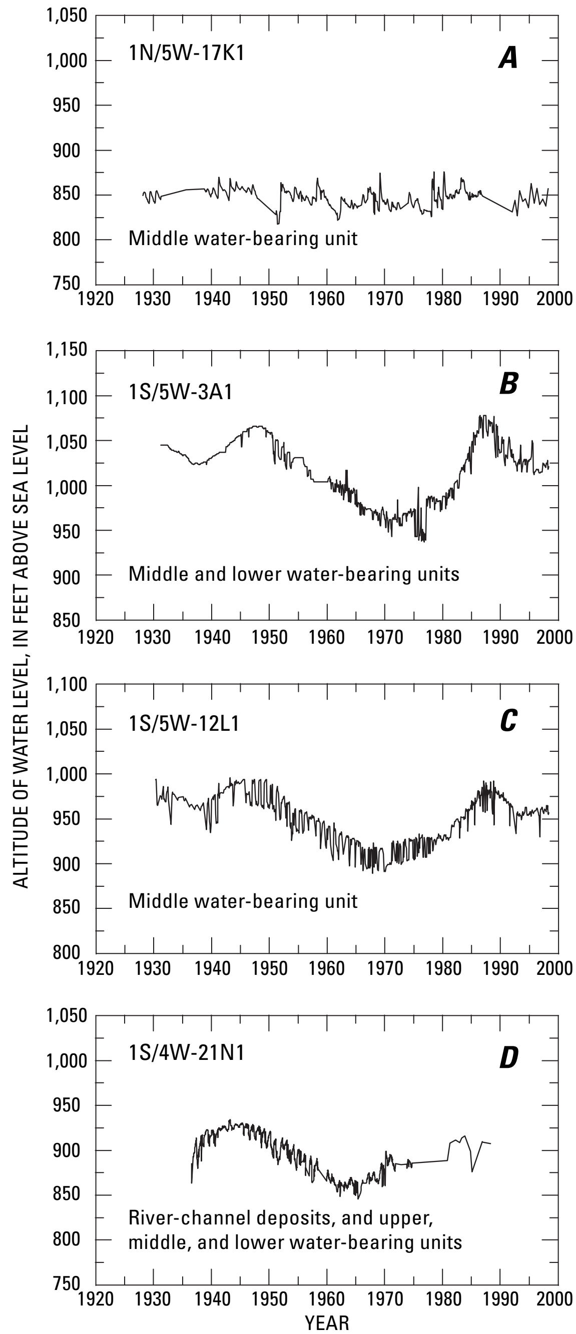


Figure 10. Water-level altitude in selected production wells, 1928–98, in the Rialto–Colton Basin, San Bernardino County, California.

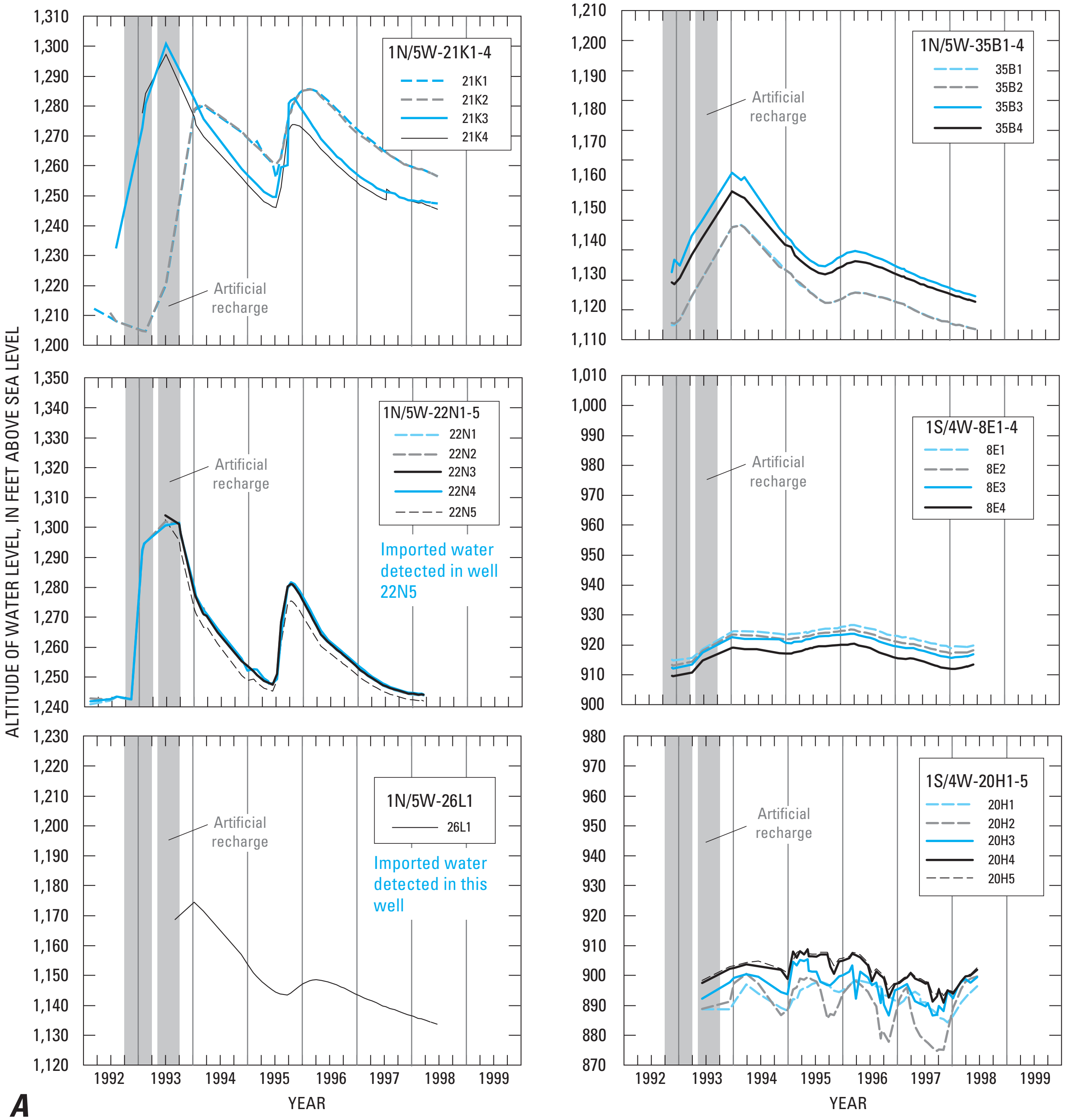


Figure 11. Water-level altitude in selected observation wells along a flowpath through Linden Ponds artificial-recharge site ***(A)***, and in other parts of the basin southwest of the unnamed fault ***(B)***, 1992–98, in the Rialto–Colton Basin, San Bernardino County, California.

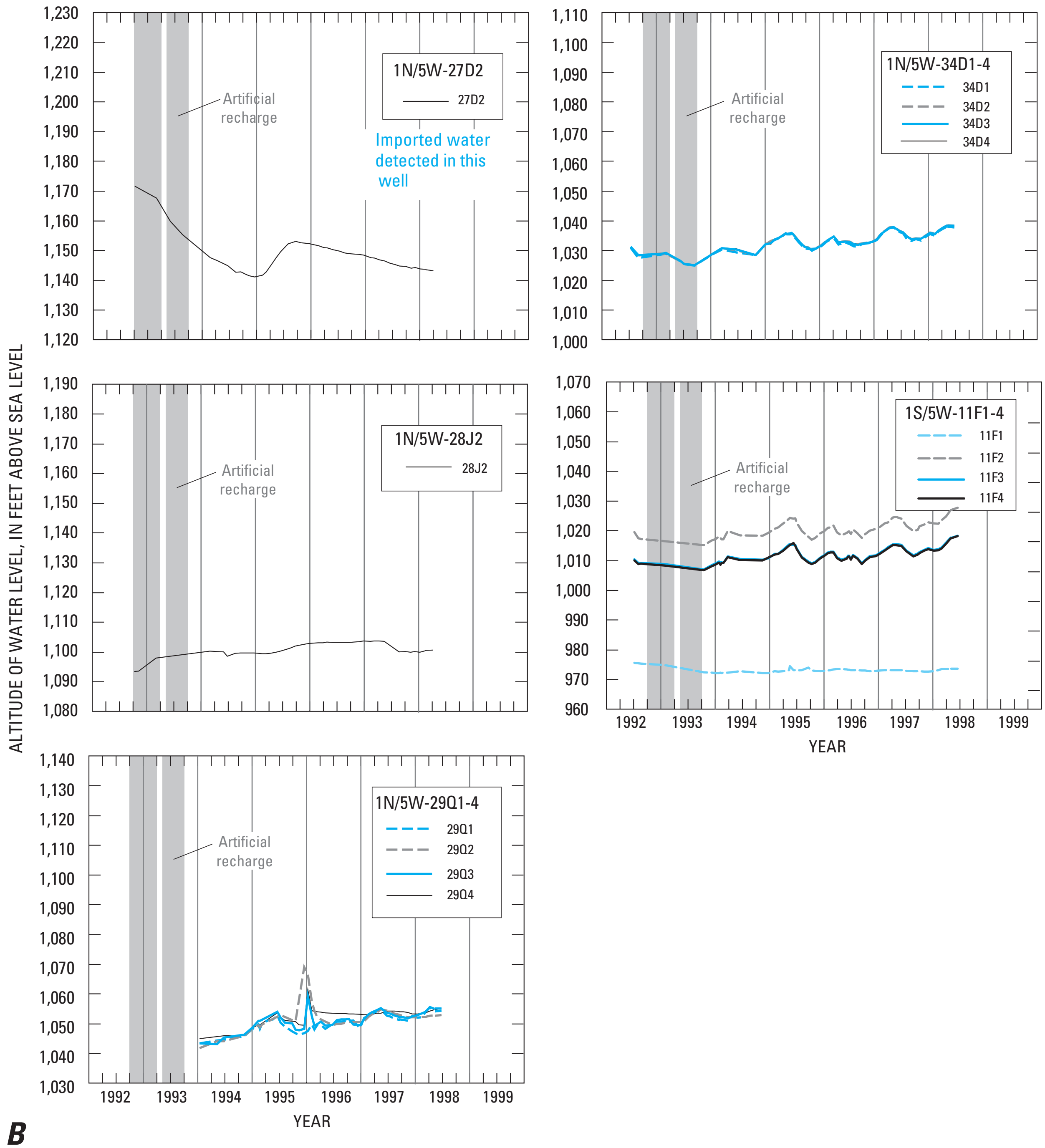


Figure 11.—Continued.

10), indicating that the ground-water systems northwest and southeast of Barrier J are not well connected.

Water levels for 1992–98 in observation wells installed for this study are shown in figure 11. During 1992–95, water levels in all wells east of the unnamed fault (1N5W-21K1-4, 1N/5W-22N1-5, 1N/5W-26L1, and 1N/5W-35B1-4) (fig. 2) responded to artificial recharge at Linden Ponds and recharge from Lytle Creek. Because artificially recharged imported water was detected in only two of the wells east of the unnamed fault (1N/5W-22N5 and 1N/5W-26L1) (Woolfenden, 1994), the rise in water levels in the other 21 wells monitored probably resulted from a pressure response to the recharge of imported water and surface runoff, indicating that the ground-water system in this part of the basin is partly confined (Woolfenden and Kadhim, 1997). During 1996–98, water levels in wells 1N/5W-21K1-4 declined rapidly but remained above 1992 levels (fig 11). During the same period, water levels in wells 1N/5W-22N1-5 declined rapidly, reaching water levels similar to those in 1992 prior to artificial recharge; and in 1N/5W-35B1-4, water levels declined less rapidly than in wells 1N/5W-22N1-5 to below pre-artificial-recharge levels (fig. 11). Water levels in wells 1S/4W-8E1-4 declined slowly during 1996–97, and the rate of decline increased slightly in 1998 (fig. 11).

During 1992–95, with the exception of well 1N/5W-27D2 in which imported water was detected, water levels in cluster wells west of the unnamed fault showed little change (wells 1N/5W-29Q1-4, 1N/5W-34D1-4, and 1S/5W-11F2-4 in figure 11). Although water levels in wells 1S/4W-20H1-5 west of the unnamed fault rose slightly at various times after artificial recharge began in 1992, it could not be determined if these water-level responses resulted from the 1992–93 artificial-recharge period, an increase in natural recharge, and (or) a decrease in pumping (Woolfenden and Kadhim, 1997). During 1996–98, water levels fluctuated in wells 1N/5W-29Q1-4, 1N/5W-34D1-4, and 1S/5W-11F2-4; however, the overall trend was upward (fig. 11). The water level in well 1S/5W-11F1 does not respond significantly to stresses on the ground-water system because it is perforated in the consolidated deposits, which are not well-connected hydraulically to the overlying units at this site (Woolfenden and Kadhim, 1997, fig. 11). At cluster site 1S/4W-20H1-5, which is southwest of the unnamed fault, water levels in wells, although fluctuating, showed a declining trend during 1996–97 and a rising trend in 1998 (fig. 11).

Table 1. Estimated annual recharge in the Rialto–Colton Basin, San Bernardino County, California, for various periods during 1935–96

[Recharge values are in acre-feet; —, no estimate or data]

Recharge source	1936–49 (Dutcher and Garrett, 1963)	1935–60 water years (California Department of Water Resources, 1970)	1945–86 (Hardt and Hutchinson, 1981)	1945–96 (W.R. Danskin, USGS, oral commun., 1997)	1980–87 (Geosciences Support Services, Inc., 1994)	1978–94 (Geosciences Support Services, Inc., 1994)	1945–96 (Woolfenden and Kadhim, 1997)
Underflow from Bunker Hill basin to Rialto–Colton Basin	14,300–23,700	3,900–16,900	15,000	868–12,087	—	—	—
Underflow from Lytle Basin to Rialto–Colton Basin	4,000	3,700–4,200	—	500	1,493–2,274	6,800	—
Ungaged runoff							
San Gabriel Mountains	—	—	—	—	—	—	300–8,000
The Badlands	—	—	—	—	—	—	0–1,000
Subsurface inflow from the San Gabriel Mountains	—	—	—	—	—	1,200	—
Imported water	—	—	—	—	—	—	0–5,345
Areal recharge of rainfall	—	—	—	—	—	28–21,000	—
Irrigation return flow	—	—	—	—	—	—	2,600–7,500

Recharge

The primary sources of recharge to the Rialto–Colton ground-water system are underflow from Bunker Hill Basin across the San Jacinto Fault in the southeastern part of the basin and underflow from Lytle Basin across Barrier E in the northwestern part; ungaged runoff in small streams that drain the San Gabriel Mountains and the Badlands, and subsurface inflow from the San Gabriel Mountains; artificial recharge from imported water; irrigation return flow; seepage loss from the Santa Ana River and its tributaries, and from the diversion canal; and areal recharge of rainfall.

Estimates of underflow from Bunker Hill Basin and Lytle Basin to the Rialto–Colton Basin have been made by previous investigators for various time periods. Estimation methods included the use of Darcy's law (Dutcher and Garrett, 1963), calibration of a ground-water flow model (California Department of Water Resources, 1970; Hardt and Hutchinson, 1980), and log-linear regression of estimated flows with water-level altitudes in a well (1S/4W-3Q1) in the Bunker Hill Basin (W. R. Danskin, USGS, written commun., 1997). Estimates of annual underflow from the Bunker Hill Basin to the Rialto–Colton Basin are given in table 1.

Several estimates of underflow from the Lytle Basin to the Rialto–Colton Basin across Barrier E were made by previous investigators. Estimation methods included the use of Darcy's law (Geosciences Support Services Inc., 1992, 1994, and Dutcher and Garrett, 1963), and calibration of a ground-water flow model (California Department of Water Resources, 1970). Estimates of annual underflow are given in table 1.

Estimates of ungaged runoff from the San Gabriel Mountains and the Badlands and subsurface inflow from the San Gabriel Mountains also are given in table 1. Estimated ungaged runoff in the San Gabriel Mountains for 1945–94 reported by Woolfenden and Kadhim (1997) ranged from about 300 acre-ft in 1994 to about 8,000 acre-ft in 1969. Estimated ungaged runoff in the Badlands reported by Woolfenden and Kadhim (1997) ranged from about 1,000 acre-ft in 1993 to no runoff during 1988–90. Estimated ground-water inflow from the San Gabriel Mountains was estimated by Geosciences Support Services, Inc. (1994), to be about 1,200 acre-ft during 1978–94. The quantity of ground-water inflow from the Badlands has not been estimated.

The quantity of water imported for artificial recharge varied between 1982, when artificial recharge began, and 1994 (fig. 12), after which it was discontinued. During 1990–91, the total quantity of imported water recharged was less than 500 acre-ft (fig. 12) owing to a statewide drought during 1986–92. Quantities of imported water recharged ranged from 5,345 acre-ft in 1986 to 65 acre-ft in 1990 (fig. 12).

Irrigation return flow from pumped wells is the quantity of pumped water that is returned to the ground-water system. Water is returned to the ground-water system as a result of percolation of excess water (water left after evaporation and transpiration) from crop irrigation and excess water from domestic or municipal irrigation of lawns, parks, and golf courses. Hardt and Hutchinson (1980) estimated excess-water return flow in the San Bernardino area to be 30 percent of annual pumpage from all sources. On the basis of reported annual pumpage from 1947 to 1994, annual recharge from irrigation return flow was estimated by Woolfenden and Kadhim (1997) to have ranged from about 2,600 to about 7,500 acre-ft (table 1). On the basis of the pumpage data used for this report (described in the "Pumpage" section), annual recharge from irrigation return ranged from about 1,400 to 5,000 acre-ft.

Areal recharge from precipitation occurs when rainfall infiltrates the land surface and percolates past the root zone to the water table; it generally is a small fraction of the total precipitation. Estimates of rainfall potentially available for recharge reported by Geosciences Support Services, Inc. (1994), range from 28 to 21,000 acre-ft/yr during 1978–94 (table 1). Areal recharge was applied to the entire basin for this report.

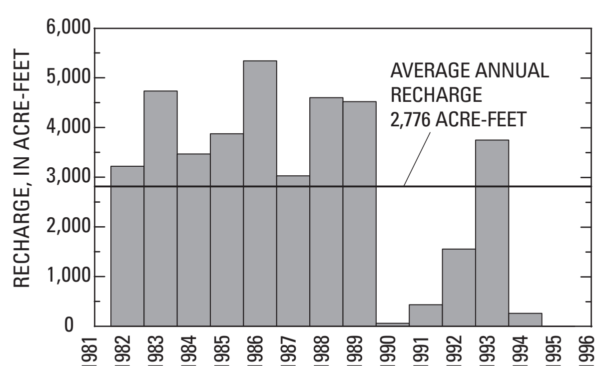


Figure 12. Annual recharge of imported water in the Rialto–Colton Basin, San Bernardino County, California, 1982–96.

The areal recharge from precipitation estimate (described in the "Areal Recharge of Rainfall" section) for the basin is about 870 acre-ft/yr.

Seepage loss from the Santa Ana River, Warm Creek, and the diversion canal near Warm Creek (fig. 2) were not estimated by previous investigators referenced for this report. Estimates of seepage loss were obtained through calibration of the ground-water flow model described in the "Numerical Simulation of Ground-Water Flow" section of this report. Estimates made for this report are described in the "Recharge" subsection ("Flow-Model Construction" section).

Discharge

The major components of ground-water discharge in the Rialto–Colton Basin include pumpage; underflow across the Rialto–Colton Fault to the Chino and North Riverside Basins; evapotranspiration by phreatophytes along Warm Creek and the Santa Ana River; and seepage to the Santa Ana River and Warm Creek during wet years when water levels in the upper water-bearing unit and river-channel deposits rise above the base of the streambed. A major component of ground-water discharge for the period 1945–96 has been pumpage. Annual pumpage ranged from 16,675 acre-ft in 1992 to 4,638 in 1982. Average annual pumpage for the period 1945–96 was 11,076 acre-ft/yr (fig. 13). Recent (late 1980's to 1996) average pumpage was higher, about 15,000 acre-ft, owing, in part, to drought conditions during 1987–92. Pumpage data were not available for 1945–46, but pumpage is assumed for the purposes of this report to be equal to the 1947 pumpage. Values plotted in figure 13 are verified pumpages from the Watermaster at Western Municipal Water District (written commun., 1998). Pumpage data for 1947–94 given by Woolfenden and Kadhim (1997) included unverified data and thus reflect somewhat different pumpage values. Also, the unverified data set included diversion values during 1945–55 that were treated separately for this phase of the study. Diversion values ranged from 15 acre-ft in 1955 to 14,000 acre-ft in 1947. Estimates of underflow were simulated with the ground-water flow model and are described in the "Simulated Water Budgets" section of this report. Evapotranspiration by phreatophytes was estimated to be about 600 acre-ft/yr for 1945–96 (Woolfenden and Kadhim, 1997). Ground water discharges to the Santa Ana River and Warm Creek when water-level altitudes in the aquifer underlying them exceed the altitudes of their streambeds. Seepage from the ground-water system to the Santa Ana River and

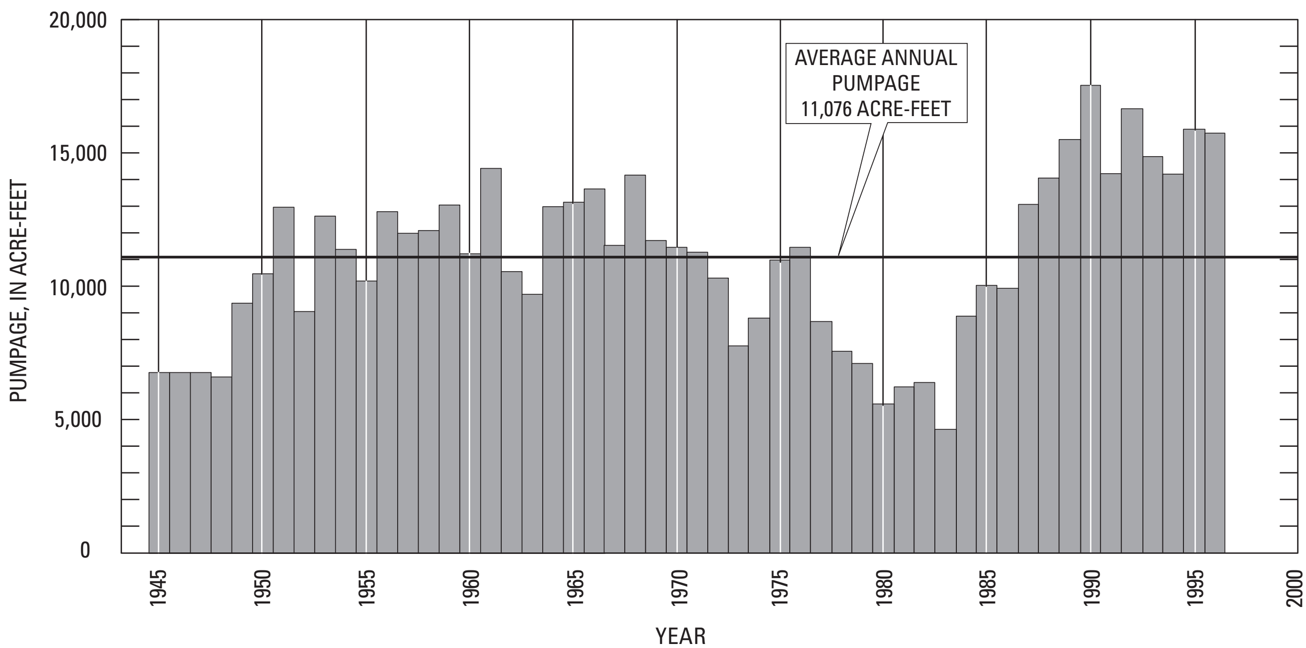


Figure 13. Annual pumpage in the Rialto–Colton Basin, San Bernardino County, California, 1945–96. (Data provided by the Watermaster at Western Municipal Water District.)

Warm Creek is computed as part of the ground-water flow model. The estimates are described in the "Simulated Water Budgets" section of the report.

NUMERICAL SIMULATION OF GROUND-WATER FLOW

Conceptual Model

The conceptual model of the Rialto–Colton ground-water basin is based on known and estimated physical and hydrologic characteristics of the ground-water flow system, and the conceptual model, in turn, forms the basis for the ground-water flow model. The physical characteristics of the study area are the boundaries of the basin (described earlier), the initial hydraulic-head distribution (for the transient model), and the types, location, and quantities of recharge and discharge (system stresses). Hydrologic characteristics simulated for the basin include those that reflect the ability of the system to transmit water (hydraulic conductivity and thickness); to store and release water (storage coefficient and specific yield); to allow for vertical passage of water between model layers (vertical conductance); and to control the flow of water across fault boundaries (hydraulic characteristic and general-head boundary conductance).

Assumptions

A numerical model is only an approximation of the natural system because not all the characteristics of the natural system are known and can be included in sufficient detail for an exact representation. Simplifying assumptions are required to make the problem manageable. Some of the more important simplifying assumptions made for this study include:

1. The aquifer system can be represented by four layers. Each model layer corresponds to the water-bearing units described earlier in the "Description of Aquifer System" section of this report.
2. The middle water-bearing unit was simulated as a single layer. However, two layers may be a more accurate conceptual representation of this part of the ground-water flow system. In the northwestern half of the basin south of Barrier J, a sandy clay unit separates the middle water-bearing unit into an upper member and a lower member; data were not available to simulate the upper member as a separate unit.
3. Ground-water movement within a layer is horizontal, and movement between layers is vertical. This assumption is a consequence of the vertical discretization used in the model (McDonald and Harbaugh, 1988, chap. 2, p. 31). Although ground-water flow generally is neither fully horizontal nor fully vertical in the actual system, this assumption adequately represents the large-scale flow regime.
4. The water-bearing layers are horizontally isotropic. Isotropy refers to the property of a medium to exhibit no directional preference in a physical process, such as the conductance of flowing water. Isotropic characteristics are difficult to determine in natural ground-water flow systems owing to the complex nature of basin geometry and potential for boundary effects that can mask isotropy or emulate anisotropy. In 1996, there were no data to suggest that large-scale anisotropic exist in the Rialto–Colton ground-water basin.
5. The hydraulic connection between the major water-bearing units can be simulated by assigning a vertical conductance between layers.
6. Changes in ground-water storage in the model layers occur instantaneously with changes in hydraulic head. In most natural ground-water flow systems, there is a delayed response to storage changes as the various materials that make up a ground-water basin release water at differing rates.
7. Recharge from ungaged runoff and subsurface inflow, underflow, and imported water occurs instantaneously. It is assumed that recharged water reaches the water table in the same year in spite of a large unsaturated zone in some areas (for example, in the vicinity of Linden Ponds). In reality, the water may take more than a year to reach the water table. This assumption does not significantly affect model-calculated heads for long-term simulations.
8. Faults internal to the flow system can be simulated adequately by horizontal-flow barriers (Hsieh and Freckleton, 1993) that impede the flow of ground water within the Rialto–Colton Basin. Faults in the Rialto–Colton Basin are steeply dipping or vertical and are known to affect water levels and movement. These conditions, and the assumption

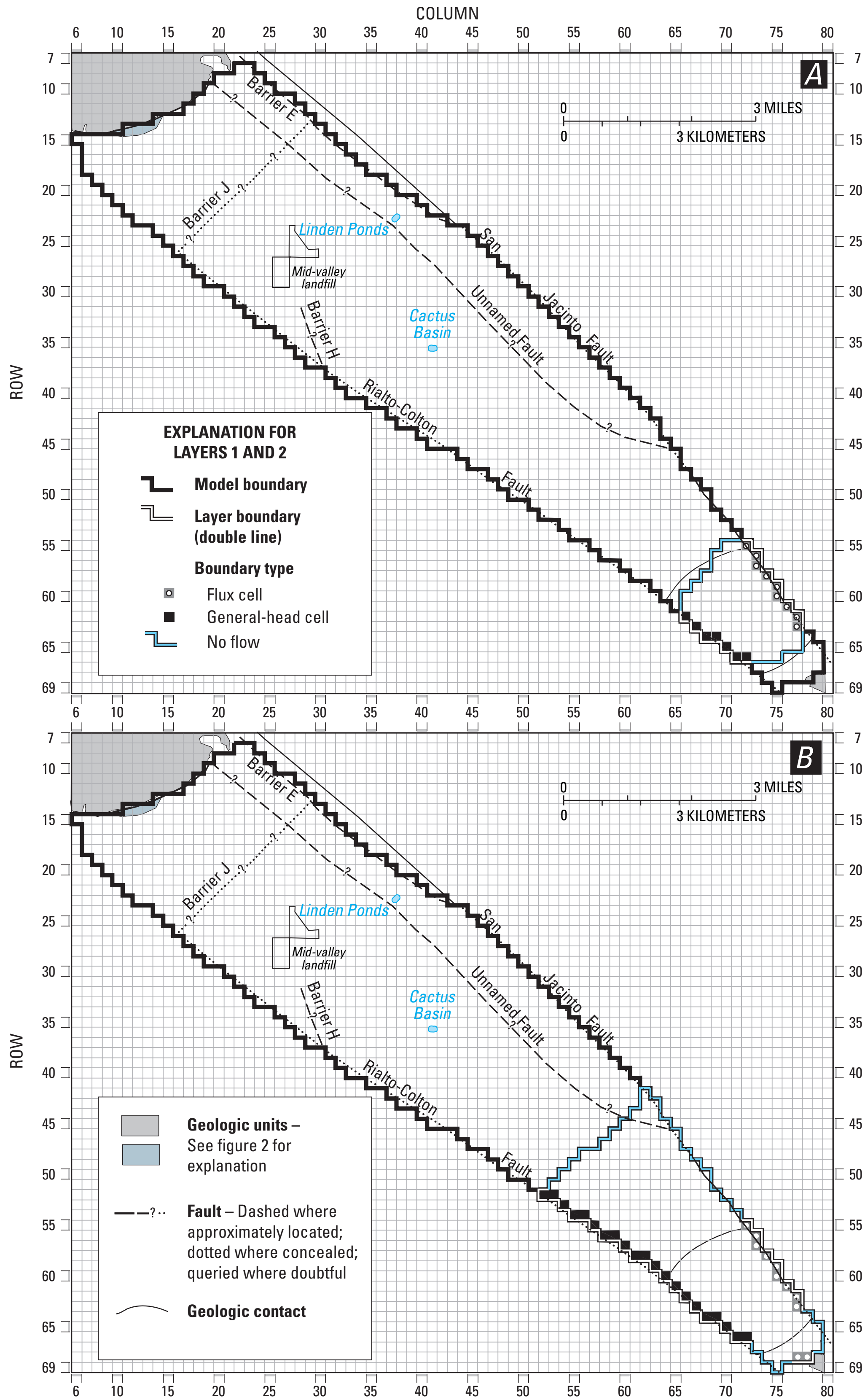


Figure 14. Model grid and boundary conditions for layers 1–4 of the Rialto–Colton Basin ground-water flow model, San Bernardino County, California.

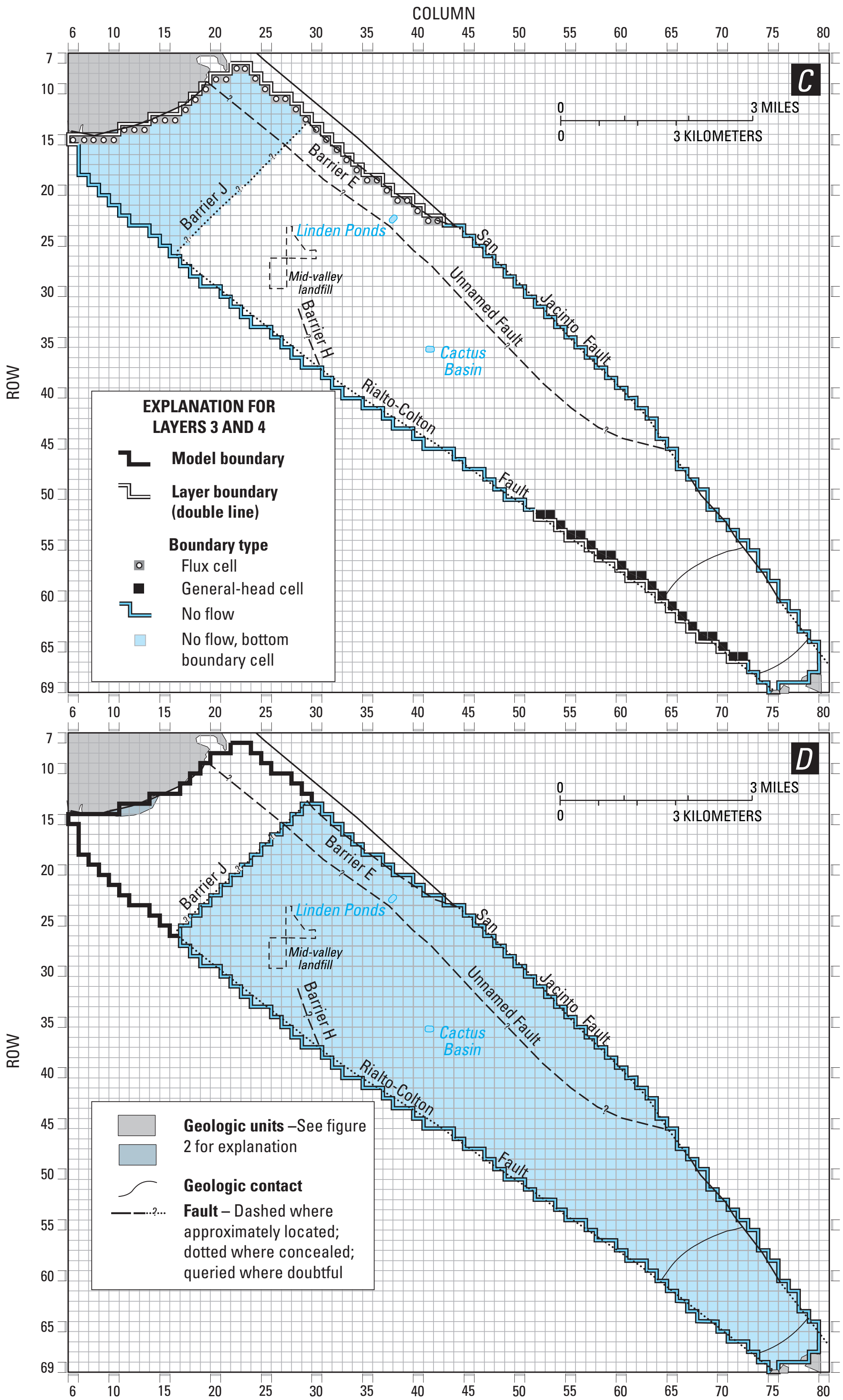


Figure 14.—Continued.

of horizontal flow (assumption number 2), conform to the criteria described by Hsieh and Freckleton (1993) for modeling with horizontal-flow barriers.

9. Underflow from the Lytle Basin to the Rialto–Colton Basin can be estimated as a percentage of discharge in Lytle Creek and can be adjusted through model calibration. This assumption is based on the water-level response to discharge in Lytle Creek reported by Woolfenden and Kadhim (1997). Data show that water levels during 1928–96 responded quickly to peak discharges in Lytle Creek.
10. Underflow from the Bunker Hill Basin to the Rialto–Colton Basin can be estimated using Darcy's Law. This assumption states that the quantity of underflow from the Bunker Hill Basin can be calculated using the annual spring hydraulic gradients across the southeastern part of the Rialto–Colton Basin, the average hydraulic conductivities of layers 1 and 2, and an estimate of the boundary area across which the underflow occurs.
11. Irrigation-return flow is assumed to be constant at 30 percent of pumpage for the entire simulation period (1945–96). Although agricultural irrigation decreased during 1945–96, it was assumed that the corresponding increase in domestic and municipal irrigation would justify use of the same return-flow factor.
12. Although the consolidated deposits are not impermeable, the quantity of water contributed by them is considered to be negligible.

Flow-Model Construction

The three-dimensional finite-difference model MODFLOW (McDonald and Harbaugh, 1988) was used to simulate flow in the Rialto–Colton Basin. In order to numerically simulate ground-water flow in the aquifer system with MODFLOW, it is necessary to (1) divide the aquifer system into a grid, (2) determine the boundary conditions, (3) estimate rates and distribution of recharge and discharge, (4) estimate the aquifer properties within the model area, and (5) discretize time of model simulation.

Model Grid

The aquifer system is divided into four horizontal layers of square cells all with side lengths (grid spacing) of about 820 ft (fig. 14). There are 90 rows and 90 columns of cells. The total number of cells is 8,100, and 2,768 of these represent the ground-water flow system. The grid spacing was chosen for consistency with an existing ground-water flow model in the adjacent Bunker Hill Basin (W.R. Danskin, USGS, written commun., 1997). Four layers were chosen to represent the four water-bearing units as described previously, and, because all water-bearing units are tapped by production wells, to account for pumpage from each unit. Layer 1 represents the river-channel deposits near the Santa Ana River and Warm Creek. Layer 1 consists of 96 active cells (fig. 14*A*). Layer 2 represents only the saturated part of the upper water-bearing unit in the southeastern part of the basin. The upper water-bearing unit in the northwestern part of the basin is unsaturated. Layer 2 consists of 296 active cells, and underlies layer 1 but extends beyond layer 1 to the southeastern boundary and to about one-third the length of the basin northwestward (fig. 14*B*). Layer 3 (middle water-bearing unit) is areally extensive throughout the model and underlies layer 2 in the southeastern one-third of the basin. Layer 3 is the only water-bearing layer represented northwest of Barrier J (fig. 14*C*) because the chemistry of water from well 1N/5W-17K2 northwest of Barrier J is similar to that of the middle water-bearing unit in the rest of the basin, and different, for the most part, from that of the other water-bearing units (Woolfenden and Kadhim, 1997). Layer 3 consists of 1,297 active cells (fig. 14*C*). Layer 4 (lower water-bearing unit) is the lowermost layer south of Barrier J; it underlies layer 3 and consists of 1,079 active cells (fig. 14*D*). All layers have variable thicknesses. Average values for the physical and hydraulic characteristics of the aquifer system within a cell area do not vary within the model cell. The model calculates the average hydraulic head within each active cell. Model cells outside the flow system are inactive and are not assigned parameter values.

Boundary Conditions

No-flow, general-head, and variable-flux boundary conditions are used to simulate the aquifer system's interaction with the regional flow system. No-flow boundaries are used around and below the modeled area to represent contact with segments of faults that act as barriers to ground-water movement between basins and contact with consolidated deposits and rocks (fig. 14). The segments of the San Jacinto Fault from its junction with Barrier E (fig. 2) to the northwestern boundary of layer 1 and from the southeastern boundary of layer 1 to the Badlands are no-flow boundaries in all layers (fig. 14). No-flow boundary conditions were assigned to the Rialto–Colton Fault from the projection of the southeastern boundary of layer 1 to the Badlands in layer 2; from the San Gabriel Mountains to the projection of the northwestern boundary of layer 2, and from the projection of the southeastern boundary of layer 1 to the Badlands in layer 3; and throughout its extent in layer 4. It was assumed that the fault is an effective barrier to ground-water movement within layers 2, 3, and 4 along these segments. The top surface of the consolidated deposits—which underlie the lower water-bearing unit (layer 4) southeast of Barrier J, and the middle water-bearing unit (layer 3) northwest of Barrier J—forms a no-flow boundary between the active ground-water flow system and the underlying deposits (fig. 14*D*).

General-head boundaries in the river-channel deposits and in the upper and middle water-bearing units where the Rialto–Colton Fault is not a barrier or a partial barrier to ground-water movement (figs. 14*A*–*C*) are used to simulate mechanisms for underflow from the Rialto–Colton Basin to the Chino and North Riverside Basins. A general-head boundary simulates a source of water outside the model area that either supplies water to, or receives water from, the adjacent cells at a rate proportional to the hydraulic-head differences between the source and the model cell (McDonald and Harbaugh, 1988, p. 11-1).

At a general-head boundary, the rate at which water is exchanged between the model cell and the outside source or sink is given by

$$Q = C(HB - h),$$

where:

- Q is the rate of flow into or out of the model cell (L^3T^{-1}),
- C is the conductance between the external source or sink and the model cell (L^2T^{-1}),
- HB is the head assigned to the external source or sink (L), and
- h is the hydraulic head within the model cell (L).

Values of C (conductance) were initially calculated from

$$C = KWb/L,$$

where:

- K is the hydraulic conductivity between the model cell and the boundary head (LT^{-1}),
- W is the cell width perpendicular to flow (L),
- b is the cell thickness (aquifer thickness) perpendicular to flow (L), and
- L is the distance between the model cell center and the specified boundary head measured parallel to flow (L).

The boundary heads (*HB*) in the river-channel deposits and in the upper and middle water-bearing units are set equal to the measured water-level altitude at wells 1S/4W-29H2 and 1S/4W-28L1 (river-channel deposits and upper water-bearing unit) (table 2). Missing water-level data for the period 1945–55 for well 1S/4W-28L1 were estimated by the linear-regression equation

$$H2 = 1.11 * H1 - 102.06,$$

where:

- $H1$ is the measured water-level altitude for well 1S/4W-29H2, and
- $H2$ is the measured water-level altitude for well 1S/4W-28L1.

The regression relation between 1S/4W-29H2 and 1S/4W-28L1 is shown in figure 15. The R^2 value, which measures the goodness-of-fit of the data for the regression relation, is 0.95. An R^2 value of 1.0 would indicate that the data were perfectly correlated. Water-level data also were not available for well 1S/4W-28H2 for 1978–81. Water levels for these years were estimated from water levels in nearby well 1S/4W-29H1 (fig. 1).

Specified-flux boundaries are used to simulate underflow from the Lytle Basin to the Rialto–Colton Basin across Barrier E in the northeast, and from the Bunker Hill Basin to the Rialto–Colton Basin across the San Jacinto Fault in the southeast (fig. 14*A*–*C*). Underflow occurs across Barrier E in layer 3 (middle water-bearing unit) both northwest and southeast of Barrier J (fig. 14*C*). Underflow occurs across the San Jacinto Fault between the northwestern and southeastern boundaries of layer 1 in both layer 1 (river-channel deposits) and layer 2 (upper water-bearing unit) (figs. 14*A*,*B*). Specified-flux boundaries are simulated in the model as injection wells with positive discharges and are input using the well package (McDonald and Harbaugh, 1988, p. 8-1, 8-2). Specified-flux values representing underflow from the Lytle Basin to the Rialto–Colton Basin are given in table 3, and those representing underflow from the Bunker Hill Basin to the Rialto–Colton Basin are given in table 4. Values for underflow from the Lytle Basin were obtained from calibration of the ground-water flow model. Values for underflow from Bunker Hill Basin were obtained from a calculation of Darcy's Law. These procedures are described further in the "Underflow" subsection ("Flow-Model Construction" section) of this report.

Recharge

Recharge to the Rialto–Colton Basin includes (1) underflow from the Lytle and Bunker Hill Basins, (2) surface spreading of imported water, (3) ungaged runoff and subsurface inflow, (4) irrigation return flow, (5) areal recharge of rainfall, and (6) seepage loss from the

Table 2. Measured and estimated water-level altitudes in wells 1S/4W-29H2 and 1S/4W-28L1, San Bernardino County, California, 1945–96

[Water-level altitudes are in feet above sea level; values for 1S/4W-28L1 in italics are estimated from regression; values for 1S/4W-29H2 in bold italics are estimated from water-level altitudes in nearby well 1S/4W-29H1]

Year	1S/4W-29H2	1S/4W-28L1	Year	1S/4W-29H2	1S/4W-28L1	Year	1S/4W-29H2	1S/4W-28L1
1945	926.6	*928.69*	1965	828.0	807.26	1985	913.8	915.26
1946	926.5	*928.58*	1966	841.0	825.26	1986	913.2	912.26
1947	925.7	*927.69*	1967	857.8	858.26	1987	906.7	904.26
1948	925.5	*927.47*	1968	858.8	861.26	1988	897.1	907.26
1949	924.8	*926.69*	1969	895.8	897.70	1989	892.5	902.26
1950	919.1	*920.35*	1970	903.2	907.26	1990	888.8	892.26
1951	893.4	*891.76*	1971	890.5	892.26	1991	888.5	*886.31*
1952	921.9	*923.46*	1972	876.2	861.26	1992	894.8	*893.32*
1953	895.2	*893.76*	1973	884.2	883.26	1993	900.5	907.26
1954	904.3	*903.88*	1974	879.6	881.26	1994	914.1	913.26
1955	895.8	*894.43*	1975	879.4	*876.20*	1995	917.6	918.26
1956	869.7	*865.39*	1976	874.9	*871.19*	1996	897.0	*895.76*
1957	871.3	870.26	1977	859.5	849.26			
1958	892.2	873.26	1978	***934.0***	*936.92*			
1959	857.1	858.26	1979	***908.1***	900.26			
1960	849.6	846.26	1980	***912.0***	899.26			
1961	829.2	830.26	1981	***912.0***	914.26			
1962	841.3	835.26	1982	912.6	906.26			
1963	831.0	*822.34*	1983	914.0	916.26			
1964	831.1	813.26	1984	914.3	*915.01*			

Santa Ana River, Warm Creek, and the diversion canal. Quantities of imported water artificially recharged in spreading basins are measured values and are used without modification in the flow model. Underflow, surface spreading of imported water, and ungaged runoff and subsurface inflow are simulated as wells with positive flux values, and are included in the MODFLOW well package construction described in detail in Appendix A. The diversion canal also is simulated as wells with a positive flux value, but the wells were not included in the well package construction described in Appendix A.

Underflow

Underflow from the Lytle Basin to the Rialto–Colton Basin across Barrier E was assigned to layer 3 in the ground-water flow model. Underflow from the Lytle Basin was distributed to 21 cells along the extent of Barrier E (fig. 14*C*). Through model calibration, it was determined that 50 percent of underflow occurred north of Barrier J, and 50 percent occurred southeast of the barrier. Initial values of underflow from the Lytle Basin to the Rialto–Colton Basin for both the initial-conditions and transient simulations were estimated by multiplying the measured discharge in Lytle Creek by a given percentage. The simulated water levels were then compared with measured water levels in well 1N/5W-17K1 north of Barrier J. Underflow values were adjusted during model calibration until simulated heads matched the measured water levels reasonably well. Discharge in Lytle Creek was multiplied by 35 percent for most years. During years in which measured discharge was at least two standard deviations above the mean (1969, 1980, 1983, and 1993), Lytle Creek discharge was multiplied by 15 percent. The model-calibrated values of underflow between the Lytle Basin and the Rialto–Colton Basin are given in table 3. This method of estimating underflow was chosen because water levels northwest of Barrier J are influenced, in part, by recharge from Lytle Creek.

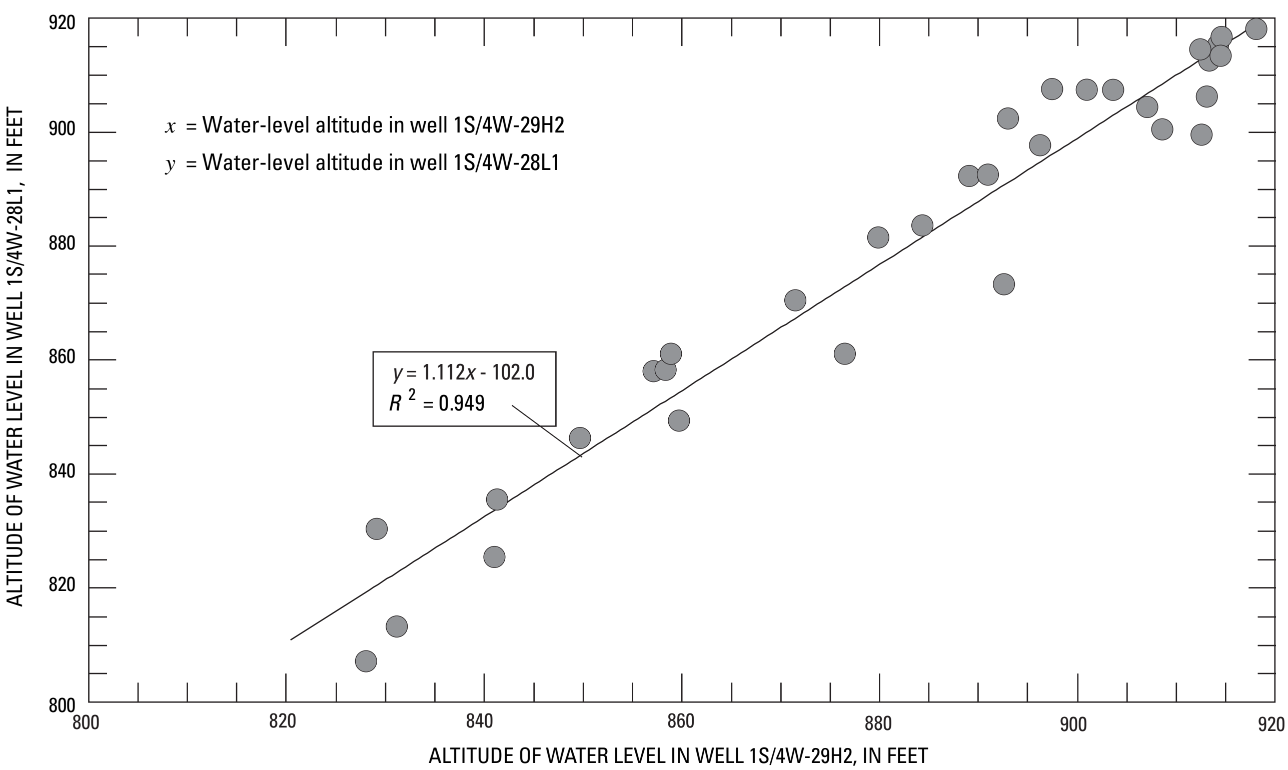


Figure 15. Relation between water-level altitude in wells 1S/4W-29H2 and 1S/4W-28L1 in the Rialto–Colton Basin, San Bernardino County, California.

Water levels in well 1N/5W-17K1 increased rapidly during periods of high discharge in Lytle Creek, remained relatively constant during periods of average discharge, and declined sharply during periods of low or no discharge (Woolfenden and Kadhim, 1997). In addition, the major-ion chemistry (calcium, magnesium, sodium, potassium, chloride, sulfate, and bicarbonate concentrations) and oxygen-18 and deuterium signatures in water from well 1N/5W-17K1 are similar to those in Lytle Creek. Detectable levels of tritium also were found in water from this well, indicating that water in that well is relatively recent (less than 44 years old) (Woolfenden and Kadhim, 1997).

Underflow from the Bunker Hill Basin to the Rialto–Colton Basin was assigned to layers 1 and 2 in the ground-water flow model on the basis of water chemistry from wells adjacent to the San Jacinto Fault and perforated at similar depths in the Rialto–Colton and Bunker Hill Basins. Water from wells perforated at depths corresponding to layers 1 and 2 on both sides of the fault had similar chemistry, and water in wells perforated at depths corresponding to layer 3 did not have similar chemistry (Woolfenden and Kadhim, 1997). Water-chemistry data for layer 4 were not available for the Bunker Hill Basin (Woolfenden and Kadhim,

Table 3. Underflow from the Lytle Basin to the Rialto–Colton Basin, San Bernardino County, California, 1945–96

[Underflow values are in acre-ft]

Year	Above Barrier J	Below Barrier J	Total	Year	Above Barrier J	Below Barrier J	Total
1945	5,478	5,478	10,956	1970	3,769	3,769	7,538
1946	5,870	5,870	11,740	1971	2,972	2,972	5,944
1947	4,529	4,529	9,058	1972	2,390	2,390	4,780
1948	2,438	2,438	4,876	1973	5,138	5,138	10,276
1949	2,058	2,058	4,116	1974	4,006	4,006	8,012
1950	1,759	1,759	3,518	1975	2,739	2,739	5,478
1951	1,495	1,495	2,990	1976	2,737	2,737	5,474
1952	6,682	6,682	13,364	1977	2,609	2,609	5,218
1953	2,391	2,391	4,782	1978	9,742	9,742	19,484
1954	3,238	3,238	6,476	1979	9,048	9,048	18,096
1955	2,412	2,412	4,824	1980	8,970	8,970	17,940
1956	2,224	2,224	4,448	1981	3,015	3,015	6,030
1957	2,363	2,363	4,726	1982	6,870	6,870	13,740
1958	9,856	9,856	19,712	1983	7,993	7,993	15,986
1959	2,980	2,980	5,960	1984	4,078	4,078	8,156
1960	1,864	1,864	3,728	1985	2,833	2,833	5,666
1961	1,404	1,404	2,808	1986	4,699	4,699	9,398
1962	3,392	3,392	6,784	1987	2,412	2,412	4,824
1963	2,107	2,107	4,214	1988	2,746	2,746	5,492
1964	1,566	1,566	3,132	1989	2,009	2,009	4,018
1965	5,932	5,932	11,864	1990	1,437	1,437	2,874
1966	7,392	7,392	14,784	1991	2,942	2,942	5,884
1967	7,975	7,975	15,950	1992	7,912	7,912	15,824
1968	3,078	3,078	6,156	1993	9,225	9,225	18,450
1969	10,890	10,890	21,780	1994	2,908	2,908	5,816
				1995	11,363	11,363	22,726
				1996	4,278	4,278	8,556

1997). Thus, the water-chemistry data suggest that underflow occurs only in layers 1 and 2.

Underflow was distributed to 18 cells, 9 in each layer (figs. 14*A, B*). The cells in both layers lie along the San Jacinto Fault between the northwestern and southeastern boundaries of layer 1 (river-channel deposits). Through model calibration, it was determined that 75 percent of underflow came from layer 1 and 25 percent from layer 2. The quantity of underflow for both the initial-conditions and transient simulations was based on calculation of Darcy's Law,

$$Q = Kai,$$

where:

Q is the volume rate of ground-water flow (L^3/t),
a is the cross-sectional area of saturated water-bearing material through which flow occurs (L^2), and
i is the hydraulic gradient (dimensionless).

The value of hydraulic conductivity used in the calculation is an average of the conductivities for layers 1 and 2. The hydraulic gradient was calculated from water levels in well 1S/4W-3Q1 in the Bunker Hill Basin and 1S/4W-29H2 in the North Riverside Basin (fig. 1). As mentioned previously in the "Boundary Conditions section," water levels for 1978–81 were

Table 4. Underflow from the Bunker Hill Basin to the Rialto–Colton Basin, San Bernardino County, California, 1945–96

[Underflow values are in acre-feet

Year	Underflow layer 1	Underflow layer 2	Total	Year	Underflow layer 1	Underflow layer 2	Total
1945	10,934	2,734	13,668	1970	5,030	1,258	6,288
1946	10,578	2,644	13,222	1971	6,495	1,624	8,119
1947	10,413	2,603	13,016	1972	7,981	1,995	9,976
1948	10,429	2,607	13,036	1973	7,657	1,914	9,571
1949	10,343	2,586	12,929	1974	8,004	2,001	10,005
1950	10,288	2,572	12,860	1975	7,862	1,966	9,828
1951	11,889	2,972	14,861	1976	8,359	2,090	10,449
1952	9,429	2,357	11,786	1977	10,253	2,563	12,816
1953	11,116	2,779	13,895	1978	5,347	1,337	6,684
1954	10,060	2,515	12,575	1979	8,920	2,230	11,150
1955	10,509	2,627	13,136	1980	9,543	2,386	11,929
1956	12,213	3,053	15,266	1981	9,969	2,492	12,461
1957	11,148	2,787	13,935	1982	10,142	2,536	12,678
1958	9,665	2,416	12,081	1983	9,643	2,411	12,054
1959	12,008	3,002	15,010	1984	12,331	3,083	15,414
1960	12,426	3,106	15,532	1985	8,766	2,192	10,958
1961	13,198	3,300	16,498	1986	7,748	1,937	9,685
1962	10,860	2,715	13,575	1987	8,175	2,044	10,219
1963	11,183	2,796	13,979	1988	7,761	1,940	9,701
1964	10,500	2,625	13,125	1989	7,368	1,842	9,210
1965	10,316	2,579	12,895	1990	7,577	1,894	9,471
1966	8,581	2,145	10,726	1991	7,149	1,787	8,936
1967	7,137	1,784	8,921	1992	6,915	1,729	8,644
1968	7,571	1,893	9,464	1993	6,925	1,731	8,656
1969	5,245	1,311	6,556	1994	5,817	1,454	7,271
				1995	5,872	1,468	7,340
				1996	7,643	1,911	9,554

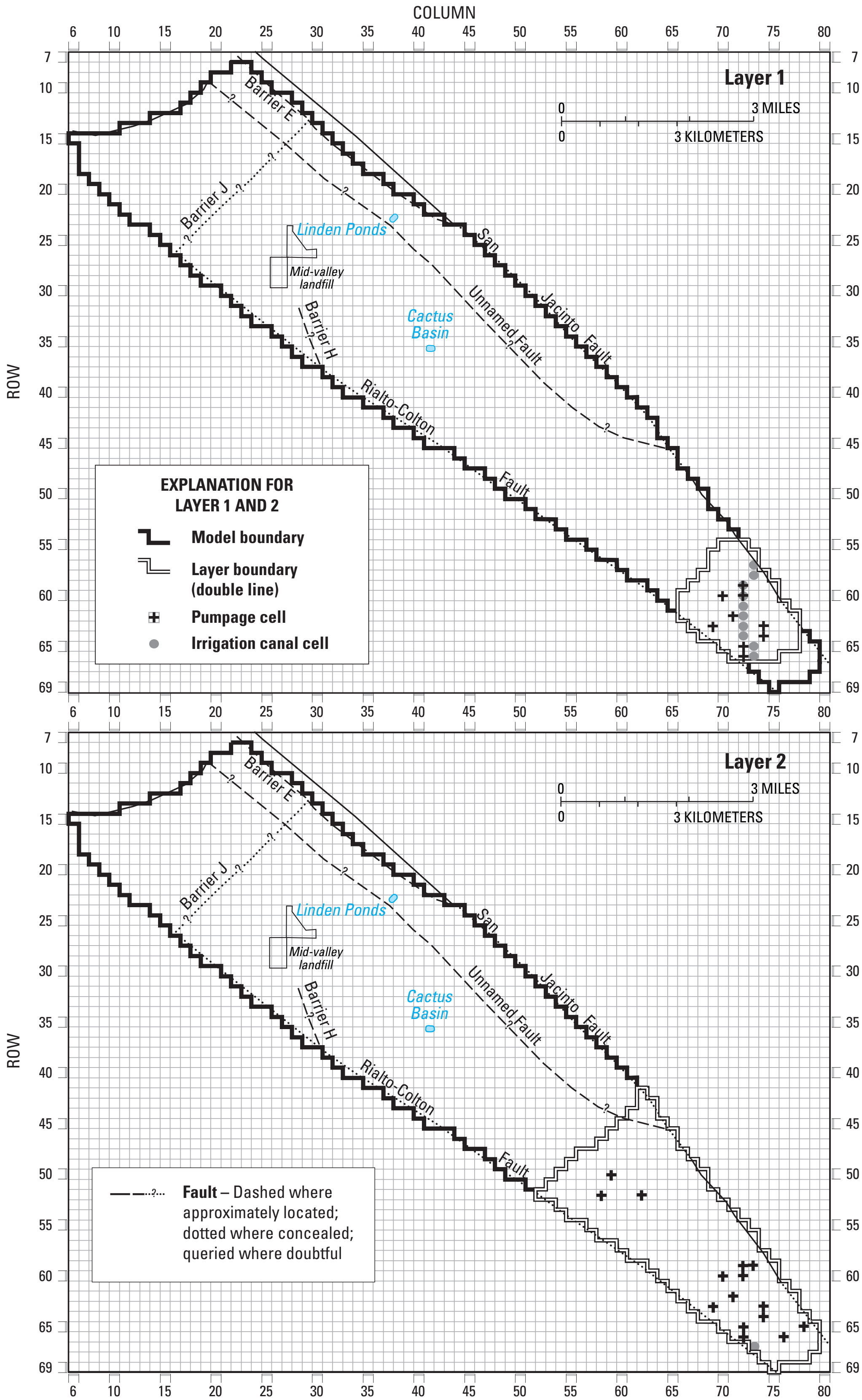


Figure 16. Model grid and areal distribution of pumpage, irrigation canal, and artificial-recharge cells for

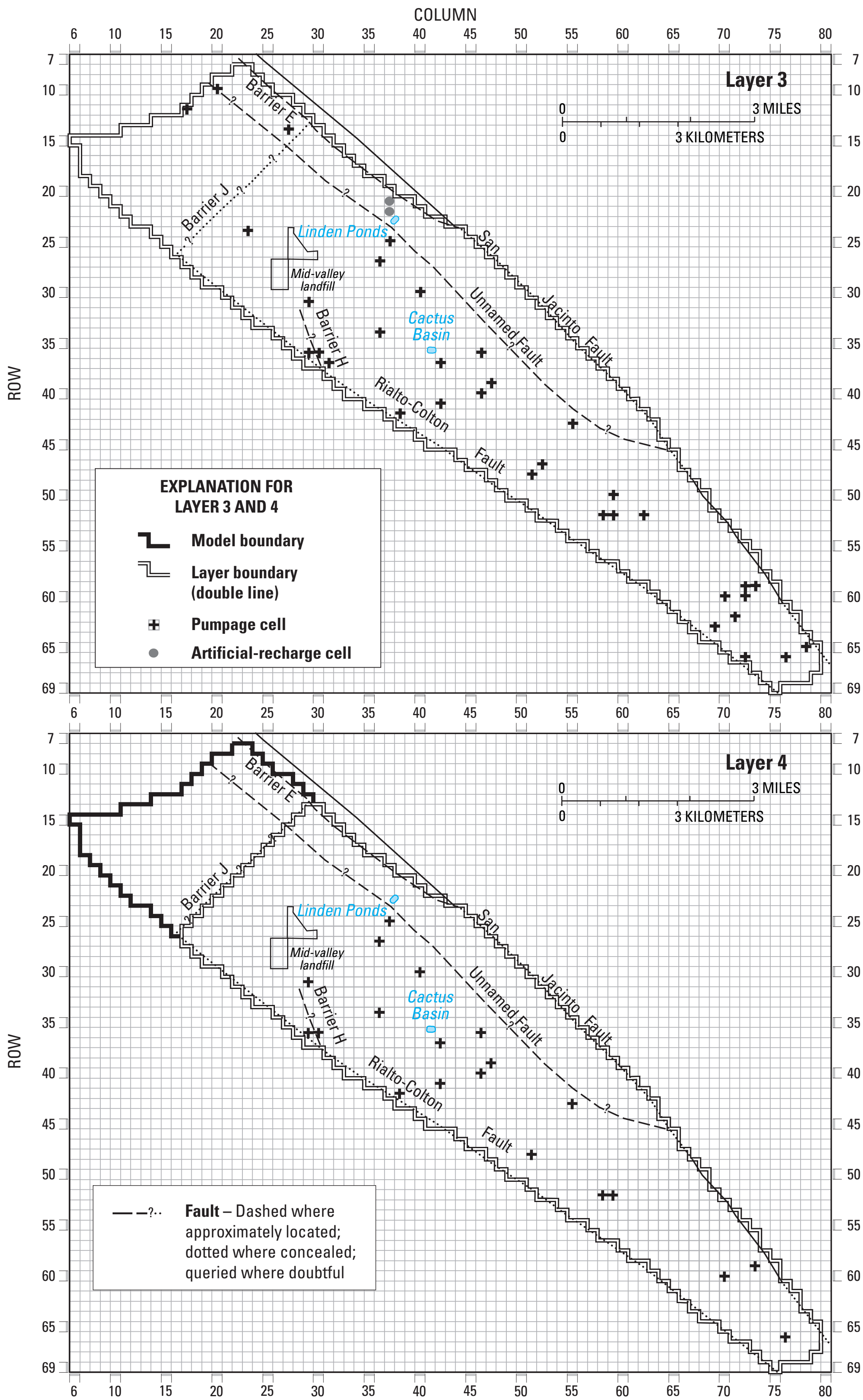


Figure 16.—Continued.

estimated from water levels in nearby well 1S/4W-29H1 (fig. 1). In 1984, water-level data were not available for 1S/4W-3Q1; consequently, underflow was estimated to be 35 percent of discharge in the Santa Ana River. Estimates of underflow from the Bunker Hill Basin are given in table 4.

Surface Spreading of Imported Water

Recharge from surface spreading of imported water at Linden Ponds was assigned to layer 3 in the ground-water flow model. This quantity was distributed equally between two cells (fig. 16) and was simulated using the well package (McDonald and Harbaugh, 1988, p. 8-1,8-2). Imported water recharged during 1982–96 is a known quantity (table 5) and therefore was not modified during model calibration. An estimate of the time it takes for the imported water to move vertically to the water table can be made using the vertical hydraulic conductivity, the porosity of layer 3, and the distance from land surface to the water table. The horizontal hydraulic conductivity used in the model is described in the "Hydraulic Conductivity" section of this report, and the vertical hydraulic conductivity is described in the "Vertical Conductance" section of this report. The vertical hydraulic conductivity is estimated to be about 0.1 times the horizontal hydraulic conductivity (Heath, 1983). The horizontal hydraulic conductivity at Linden Ponds is 0.0005787 ft/s; hence the vertical hydraulic conductivity is 0.00005787 ft/s. The porosity for layer 3 (0.30) was estimated on the basis of stable-isotope data and is described in the "Simulated Effects of Artificial-Recharge Alternatives on Ground-Water Levels and Movement" section. The distance to the water table was about 300 ft in spring 1996 (fig. 7). Thus, the time it takes for the imported water to reach the water table is calculated by [330 ft/(0.30*0.00005787 ft/s)]/(86,400 s/d), which equals about 220 days. This value was not used in the model explicitly; however, it is assumed that artificially recharged water reaches the water table in the same year in which recharge occurs. A clay lens about 360 ft below land surface impedes the farther vertical movement of the imported water (Woolfenden, 1994; Woolfenden and Kadhim, 1997).

Table 5. Quantities of imported water artificially recharged at Linden Ponds, San Bernardino County, California 1982–96

[Quantities are in acre-feet]

Year	Artificial-recharge quantity
1982	3,220
1983	4,736
1984	3,471
1985	3,879
1986	5,345
1987	3,030
1988	4,601
1989	4,522
1990	65
1991	435
1992	1,559
1993	3,747
1994	261
1995	0
1996	0

Ungaged Runoff and Subsurface Inflow

Ungaged runoff and subsurface inflow were simulated using the well package, and quantities of inflow were assigned to layer 3 at the base of the San Gabriel Mountains in the northwestern part of the model grid and to layer 2 at the base of the Badlands in the southeastern part of the model grid (fig. 14). The quantity of ungaged surface runoff is a function of the drainage areas for the small creeks and the mountain fronts. Estimates of ungaged runoff can be calculated by multiplying these drainage areas by a unit discharge value obtained from a gaged creek draining the same mountains (J.C. Bowers, USGS, oral commun., 1994). Discharge values from Lytle Creek and San Timoteo Creek were used to obtain the unit discharges for the San Gabriel Mountains and the Badlands, respectively. Ungaged runoff and subsurface inflow from the San Gabriel Mountains were distributed equally to 17 cells. Ungaged runoff and subsurface inflow from the Badlands were distributed equally to two cells (fig. 14*B*). Estimates made by Woolfenden and Kadhim (1997) for ungaged runoff were used in the model and are given in table 6. Subsurface inflow from the Gabriel Mountains was reported by Geosciences Support Services, Inc. (1994), to be 1,200 acre-ft/yr for the period 1978–93, and this value was used in the model. Subsurface inflow from the Badlands was assumed to be negligible and was not modeled. Quantities of ungaged runoff and subsurface inflow were not adjusted during model calibration.

Irrigation Return Flow

Irrigation return flow is the quantity of total pumpage returned to the aquifer. Water is returned as a result of percolation from agricultural irrigation and from some domestic and municipal uses. Irrigation return flow in the Rialto–Colton Basin was estimated to be 30 percent of total pumpage for each well on the basis of the ground-water flow model for the Bunker Hill Basin (Hardt and Hutchinson, 1980; W.R. Danskin, USGS, oral commun., 1994). Irrigation return flow was accounted for in the model by reducing pumpage by 30 percent. This method of return-flow computation does not imitate the actual process. Ground water is pumped from the different water-bearing units (layers) within the basin, whereas return flow occurs only in the uppermost unit. However, in the Rialto–Colton Basin, the middle water-bearing unit (layer 3) is the uppermost saturated unit throughout nearly two-thirds of the basin and also is the main water-producing unit in the basin (Woolfenden and Kadhim, 1997). In a simplification of the actual process, the return flow factor of 30 percent is held constant throughout the model simulation period (1945–96). Land use gradually changed from agricultural to urban between 1949 and 1993 (figs. 3 and 4), and the assumption that irrigation return from watering lawns, golf courses, parks, and other such areas would be approximately the same percentage as that from irri-

Table 6. Ungaged runoff from the San Gabriel Mountains and the Badlands, San Bernardino County, California, 1945–96

[Recharge values are in acre-feet]

Year	San Gabriel Mountains	The Badlands	Total	Year	San Gabriel Mountains	The Badlands	Total
1945	1,733	88	1,821	1971	940	32	972
1946	1,857	44	1,901	1972	756	2	758
1947	1,433	7	1,440	1973	1,626	125	1,751
1948	771	8	779	1974	1,267	31	1,298
1949	651	4	655				
				1975	866	26	892
1950	556	6	562	1976	866	41	907
1951	473	6	479	1977	825	38	863
1952	2,114	176	2,290	1978	7,192	370	7,562
1953	756	3	759	1979	2,862	295	3,157
1954	1,024	78	1,102				
				1980	6,622	728	7,350
1955	763	10	773	1981	954	40	994
1956	704	17	721	1982	2,174	143	2,317
1957	747	6	753	1983	5,900	519	6,419
1958	3,118	115	3,233	1984	1,290	59	1,349
1959	943	5	948				
				1985	896	29	925
1960	590	3	593	1986	1,487	75	1,562
1961	444	19	463	1987	763	5	768
1962	1,073	29	1,102	1988	869	0	869
1963	667	4	671	1989	636	0	636
1964	496	4	500				
				1990	455	0	455
1965	1,877	170	2,047	1991	931	14	945
1966	2,339	279	2,618	1992	2,451	61	2,512
1967	2,523	65	2,588	1993	6,251	985	7,236
1968	974	26	1,000	1994	266	78	344
1969	8,039	716	8,755	1995	2,872	641	3,513
1970	1,193	56	1,249	1996	1,353	92	1,445

gating orange groves (the main agricultural land use in 1949) may be overstated.

Areal Recharge of Rainfall

Direct infiltration of precipitation is simulated as areal recharge. Areal recharge was assigned to the uppermost active layer in the model (fig. 17) and was distributed equally to all recharge cells in the model grid. The rate of areal recharge assigned to each recharge cell was 1.38×10^{-9} ft/s (0.5 in/yr; a total of about 870 acre-ft/yr for the basin); this rate is based on a calibrated ground-water flow model for the adjacent Bunker Hill Basin (Hardt and Hutchinson, 1980). Areal recharge from rainfall was assumed constant with time.

Seepage Loss from the Santa Ana River, Warm Creek, and the Diversion Canal

Stream recharge was assigned to layer 1 in the model to cells along the Santa Ana River and Warm Creek (fig. 18), and was simulated using a model package that simulates interaction between the stream and the aquifer (Prudic, 1989, p. 1–11). Model input included stream discharge into the basin, stream width, altitudes of the top and bottom of the streambed, stream stage, and stream conductance. Discharge quantities used in the flow model are measured values and are given by Woolfenden and Kadhim (1997). Stream width was assumed to be the width of one cell (about 820 ft). The top altitude of the streambed was assumed to be the land-surface altitude at the stream, and the bottom altitude was assumed to be 5 ft lower than the top altitude. The stream stage was assumed to be 5 ft higher than the top altitude of the streambed (land-surface altitude plus 5 ft). The stream conductance was

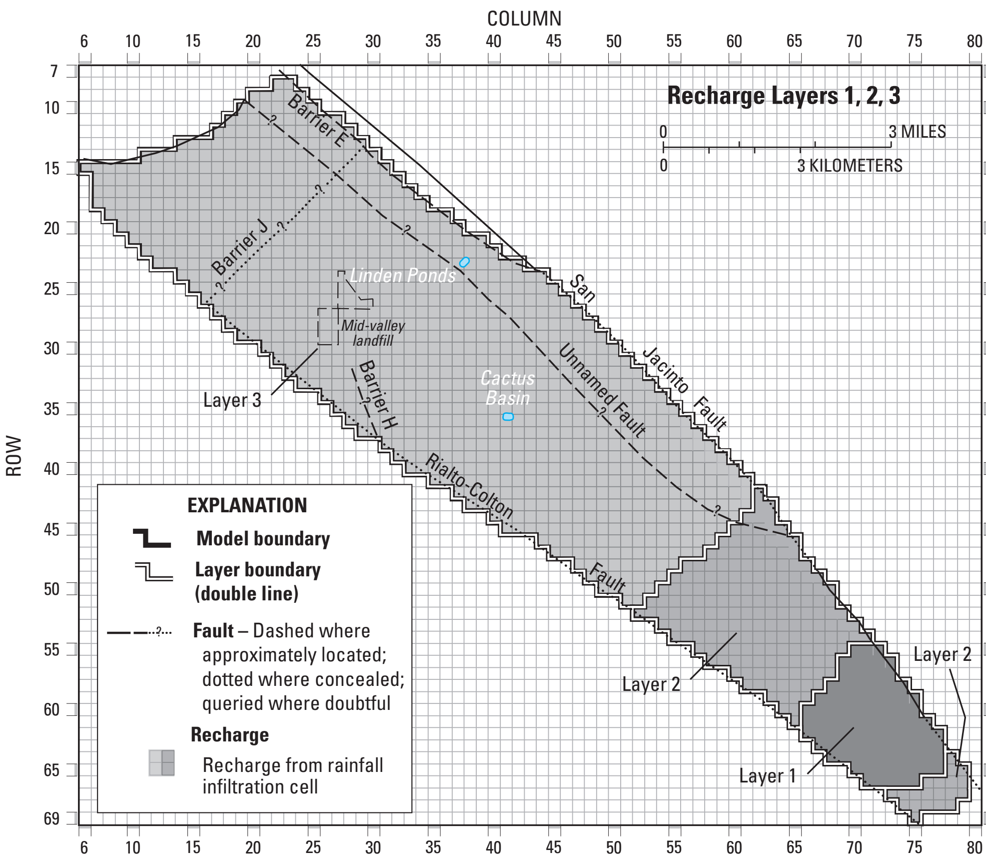


Figure 17. Model grid and areal distribution of recharge from rainfall infiltration cells for layers 1–3 of the Rialto–Colton Basin ground-water flow model, San Bernardino County, California.

assumed to be 0.1 ft^2/s. These values correspond to those determined from a calibrated flow model for the adjacent Bunker Hill Basin (W.R. Danskin, USGS, oral commun., 1994) and were not modified during model calibration.

Water was diverted from Warm Creek into an irrigation canal (fig. 2) during 1945–55. The canal has an unlined channel, and seepage was simulated as a series of wells (fig. 16) with a positive flow rate. The percentage of seepage loss in the canal was assumed to be the same as the percentage of seepage loss in Warm Creek and the Santa Ana River. Quantities of seepage loss were determined by computing a ratio between the model-generated seepage loss in Warm Creek and the Santa Ana River, and total inflow from both sources. The ratio did not vary significantly during 1945–55, and the 1945 value was used for the entire period. The measured quantity of water diverted from Warm Creek is multiplied by the computed ratio (10 percent) to determine seepage loss. The quantity of seepage loss from the canal simulated in the ground-water flow model ranged from 1,978 acre-ft in 1948 to 3 acre-ft in 1955 (table 7).

Discharge

The primary components of ground-water discharge from the aquifer system are (1) pumpage, (2) underflow from the Rialto–Colton Basin to the Chino Basin, (3) evapotranspiration from bare soil and of phreatophytes along the Santa Ana River and Warm Creek, and (4) seepage loss from the aquifer to the Santa Ana River and Warm Creek. Seepage loss from the aquifer to the Santa Ana River and Warm Creek was simulated in the same manner as discussed in the "Recharge" subsection ("Flow-Model Construction" section) for seepage from the Santa Ana River and Warm Creek to the aquifer and is not discussed in this

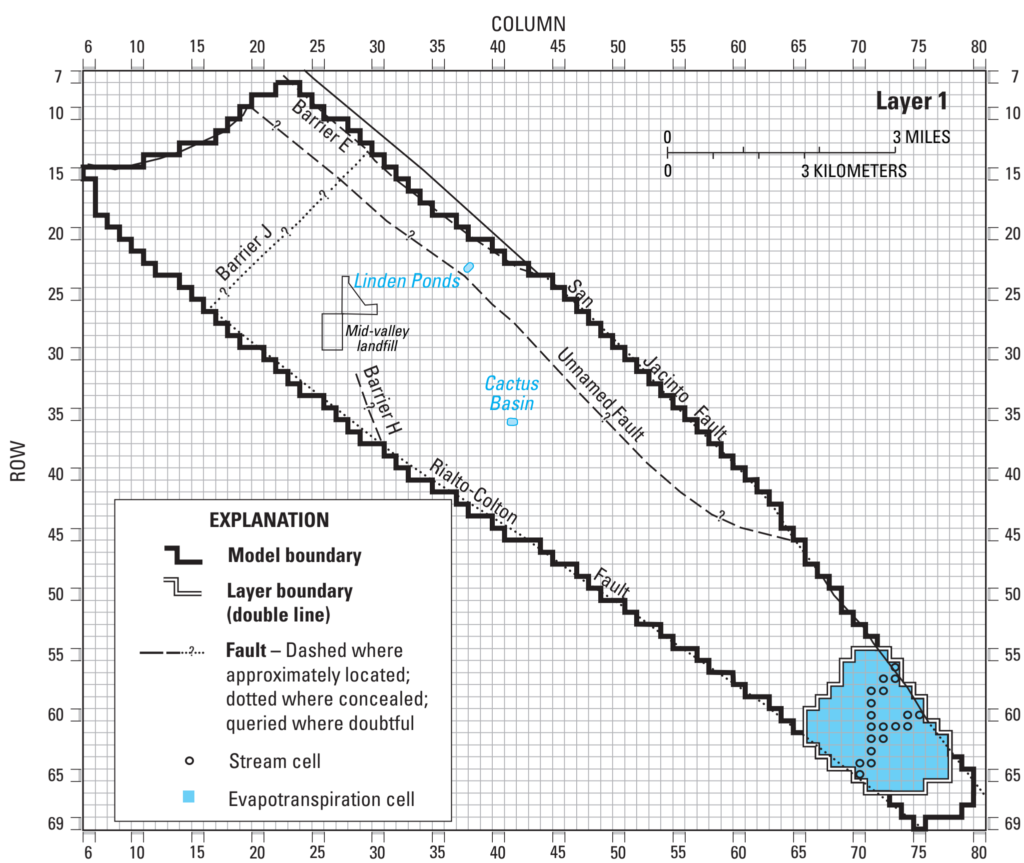


Figure 18. Model and areal distribution of stream and evapotranspiration cells for layer 1 of the Rialto–Colton Basin ground-water flow model, San Bernardino County, California.

Table 7. Seepage loss in the diversion canal, San Bernardino County, California, 1945–55

[Quantities are in acre-feet]

Year	Seepage loss
1945	1,123
1946	1,260
1947	1,404
1948	1,978
1949	1,326
1950	1,116
1951	669
1952	230
1953	378
1954	132
1955	3

section. The values of stream discharge into the basin, stream width, top and bottom altitudes of the streambed, stream stage, and stream conductance are the same as those discussed in the previous section.

Pumpage

Ground-water pumpage is a major discharge in the Rialto–Colton Basin. A total of 47 wells were pumped at some time during the period 1945–96 (fig. 16). Pumpage from individual wells in the Rialto–Colton Basin has been reported to and verified by the Santa Ana River Watermaster since 1947, and is managed by the Western Municipal Water District. Because land-use and hydrologic conditions during 1945–46 were similar to those of 1947, pumpage for

Table 8. Annual total and net pumpage from the Rialto–Colton Basin, San Bernardino County, California, 1945–96

[Pumpage values are in acre-feet; net pumpage values equal total pumpage minus irrigaton return flow]

Year	Total Pumpage	Net Pumpage	Year	Total Pumpage	Net Pumpage
1945	6,791	4,754	1970	11,469	8,028
1946	6,791	4,754	1971	11,293	7,905
1947	6,791	4,754	1972	10,319	7,223
1948	6,630	4,641	1973	7,763	5,434
1949	9,400	6,580	1974	8,817	6,172
1950	10,496	7,347	1975	11,002	7,701
1951	12,995	9,096	1976	11,470	8,029
1952	9,093	6,365	1977	8,688	6,082
1953	12,672	8,870	1978	7,571	5,300
1954	11,416	7,991	1979	7,103	4,972
1955	10,242	7,169	1980	5,595	3,916
1956	12,839	8,987	1981	6,237	4,366
1957	12,018	8,413	1982	6,402	4,481
1958	12,122	8,485	1983	4,638	3,247
1959	13,092	9,164	1984	8,892	6,224
1960	11,244	7,871	1985	10,051	7,036
1961	14,471	10,130	1986	9,932	6,952
1962	10,580	7,406	1987	13,085	9,160
1963	9,732	6,812	1988	14,076	9,853
1964	13,029	9,120	1989	15,526	10,868
1965	13,186	9,230	1990	17,551	12,286
1966	13,684	9,579	1991	14,244	9,971
1967	11,543	8,080	1992	16,675	11,672
1968	14,184	9,929	1993	14,892	10,424
1969	11,729	8,210	1994	14,227	9,959
			1995	15,922	11,145
			1996	15,758	11,031

1945–46 was assumed to be the same as that of 1947. Reported and estimated annual (total and net) pumpage values are given in table 8.

Net pumpage is used in the model and was not modified during calibration. Irrigation return flow is accounted for in the model by calculating net pumpage (the total pumpage minus the quantity of water that is returned to the system). As stated in the "Irrigation Return Flow" section of this report, the return-flow factor is 30 percent, and net pumpage values are, therefore, 70 percent of total pumpage values.

Pumpage is assigned to layers on the basis of the length of the perforated interval of a well within a given water-bearing unit and the hydraulic conductivity of that water-bearing unit. ARC/INFO AML (Arc Macro Language) programs were developed to compute net pumpage from total pumpage and to assign net pumpage to individual model layers (the water-bearing unit and designated layers described in the "Model Grid" section), and to create MODFLOW-readable well packages (see Appendix A). ARC/INFO is a geographic information system from Environmental Systems Research Institute, Inc. (ESRI), of Redlands, California.

The AML programs assign pumpage vertically using top and bottom altitudes of perforated intervals, land-surface altitudes, top and bottom altitudes of model layers, and the hydraulic conductivity of the model layer to calculate the percentage of pumpage contributed by each layer. Percentages calculated by the ARC/INFO programs are given in table 9. The vertical pumpage distribution is computed by multiplying the net pumpage for a well by the percentages mentioned above. The method is described by

$$q(net)=q(n) * pcnt\_ir / 100,$$
$$q(n) = QT * pcnt(n), \text{ and}$$
$$pcnt(n)= [L(n)*k(n)][L(1)*k(1)+L(2)*k(2)+\ldots+L(n)*k(n)],$$

where:

- *q(n)* is the total pumpage assigned to model layer n (ft^3/s),
- *n* is the model layer number,
- *pcnt_ir* is the irrigation efficiency (the remainder is the return flow),
- *QT* is the total pumpage of a given well (ft^3/s),
- *pcnt(n)* is the percentage of total pumpage assigned to layer n,
- *L(n)* is the length of perforated interval of a well in model layer n (ft), and
- *k(n)* is the hydraulic conductivity in model layer n (ft/s).

Total pumpage for reported years 1945–96 is computed as

$$QT = [Yr * -0.0013813\ (ft^3/s)/\text{acre-ft}] * (pcnt\_qt / 100),$$

where:

- *Yr* is the total pumpage of well (acre-ft) and
- *pcnt_qt* is the percentage of pumpage to be used in the model run.

Total pumpage for the predictive simulation (1997–2027) is computed as

$$QT = [Yr * -0.0013813\ (ft^3/s)/\text{acre-ft}] * (pcnt\_qt / 100),$$

where the variables are as defined above.

Where construction data are not available or the hydrologist has better knowledge of the contributing model layer, pumpage is assigned vertically in the following manner. If perforated-interval data are not available but well depth is known, pumpage is evenly distributed to each layer the well intersects. Where no well-construction data are available, the pumpage is assigned on the basis of construction data for nearby wells or on the basis of knowledge of the basin hydrogeology. These model-layer designations are entered into the ARC/INFO data base and remain unchanged during operation of the AML programs (see Appendix A).

Underflow

Underflow from the Rialto–Colton Basin to the Chino and North Riverside Basins was assigned to layers 1, 2, and 3, with 7 cells in layer 1, and 21 cells each in layers 2 and 3 (figs. 14*A*–*C*). As mentioned previously, the effect of underflow is simulated using the general-head boundary package. Input to the package are head (described in the "Boundary Conditions" section) and conductance. Conductance values were determined during model calibration. For layer 1, the conductance values are 0.05 ft^2/s. For layers 2 and 3, the conductance values are 0.04 ft^2/s (fig. 14*C*). On the basis of water levels measured in the Rialto–Colton Basin (for example, in wells 1S/4W-20H3-5), water-level differences between layers 1, 2, and 3 typically are less than 10 ft.

Table 9. Percent of pumpage from each layer for production wells in the Rialto–Colton Basin, San Bernardino County, California

[—, well not screened in layer]

State well number	Percent layer 1	Percent layer 2	Percent layer 3	Percent layer 4
1N/5W-7P2	—	—	100	—
1N/5W-7P3	—	—	100	—
1N/5W-18D1	—	—	100	—
1N/5W-17G1	—	—	100	—
1N/5W-17K1	—	—	100	—
1N/5W-17K2	—	—	100	—
1N/5W-30A1	—	—	50	50
1N/5W-27D1	—	—	88	12
1N/5W-28J1	—	—	42	58
1N/5W-29R15	—	—	50	50
1N/5W-34B1	—	—	58	42
1N/5W-34M1	—	—	60	40
1S/5W-2C1	—	—	55	45
1S/5W-2E1	—	—	51	49
1S/5W-2G1	—	—	46	54
1S/5W-2K1	—	—	71	29
1S/5W-3A1	—	—	79	21
1S/5W-3J1	—	—	89	11
1S/5W-3N2	—	—	95	5
1S/5W-4D2	—	—	100	—
1S/5W-5A2	—	—	50	50
1S/5W-5A3	—	—	84	16
1S/5W-12A1	—	—	50	50
1S/5W-12A1	—	—	50	50
1S/5W-12L1	—	—	100	—
1S/5W-12N1	—	—	99	1
1S/4W-7C1	—	—	100	—
1S/4W-17M1	—	54	46	—
1S/4W-18B1	—	29	71	—
1S/4W-18F1	—	2	77	21
1S/4W-18G1	—	—	96	4
1S/4W-18K1	—	—	—	100
1S/4W-21K1	—	38	50	12
1S/4W-21L1	41	46	13	—
1S/4W-21N1	54	20	21	5

Table 9. Percent of pumpage from each layer for production wells in the Rialto–Colton Basin, San Bernardino County, California—Continued

State well number	Percent layer 1	Percent layer 2	Percent layer 3	Percent layer 4
1S/4W-21P1	100	—	—	—
1S/4W-21Q1	52	38	10	—
1S/4W-21Q3	—	85	15	—
1S/4W-27L1	—	44	56	—
1S/4W-27M1	—	24	68	9
1S/4W-28A6	32	68	—	—
1S/4W-28C1	23	42	34	—
1S/4W-28D1	7	66	27	—
1S/4W-28G1	98	2	—	—
1S/4W-28K1	68	24	8	—
1S/4W-28K2	93	7	—	—
1S/4W-29H3	90	10	—	—

Evapotranspiration

Evapotranspiration is assigned to all cells in layer 1 (fig. 18). The land-surface altitude, evapotranspiration rate, and extinction depth are data needed for the evapotranspiration package in the model (McDonald and Harbaugh, 1988, p. 10-1–10-7). The land-surface altitude for layer 1 was estimated from a digital elevation model (DEM). The evapotranspiration rate used in the model is 1.39 X 10^{-13} ft^3/s and the extinction depth is 15 ft. The basis for these assigned values is their use in the calibrated ground-water flow model for the adjacent Bunker Hill Basin (W. R. Danskin, USGS, oral commun., 1994).

Flow Barriers

Barrier J, the unnamed fault, and Barrier H are modeled as horizontal-flow barriers using the HFB (horizontal-flow barrier) package (Hsieh and Freckleton, 1993). Conceptually, a horizontal-flow barrier is a thin, vertical low-permeability feature, such as a fault. In the model, the feature is simulated as a series of horizontal-flow barriers situated on the boundary between pairs of adjacent cells (each relevant cell boundary is a "barrier" in the HFB package). The barrier effect is determined by the "hydraulic characteristic," which is defined to be the hydraulic conductivity divided by the barrier width (Hsieh and Freckleton, 1993). The smaller the hydraulic characteristic, the more effective the barrier is to ground-water movement.

The distribution of horizontal-flow barriers in the Rialto–Colton Basin and their hydraulic characteristics are shown in figure 19. Barrier J is modeled only in layer 3. Both the unnamed fault and Barrier H are modeled in layers 3 and 4. Hydraulic characteristics for all flow barriers were adjusted during both model calibrations. Barrier J has three segments of varying hydraulic characteristics. The hydraulic characteristic assigned to Barrier J east of the unnamed fault is smaller than that west of the fault to enable matching of simulated heads with measured water-level altitudes and to restrict the quantity of water flowing into the corridor between the unnamed fault and the San Jacinto Fault southeast of Barrier J. The hydraulic characteristic of the unnamed fault northwest of Barrier J is larger than that of the fault southeast of Barrier J, indicating that this segment of the unnamed fault is a less effective barrier than are the other segments. Southeast of Barrier J, the hydraulic characteristic of the northern half of the unnamed fault is lower than that of the southeastern half to better match simulated heads to measured water-level altitudes in the corridor between the unnamed fault and the San Jacinto Fault. The hydraulic characteristic of the unnamed fault in layer 4 is smaller than that for layer 3 for both the northern and southern segments. This is consistent with the results from analysis of stable-isotope data by Woolfenden and Kadhim (1997) that indicate greater mixing of water northeast

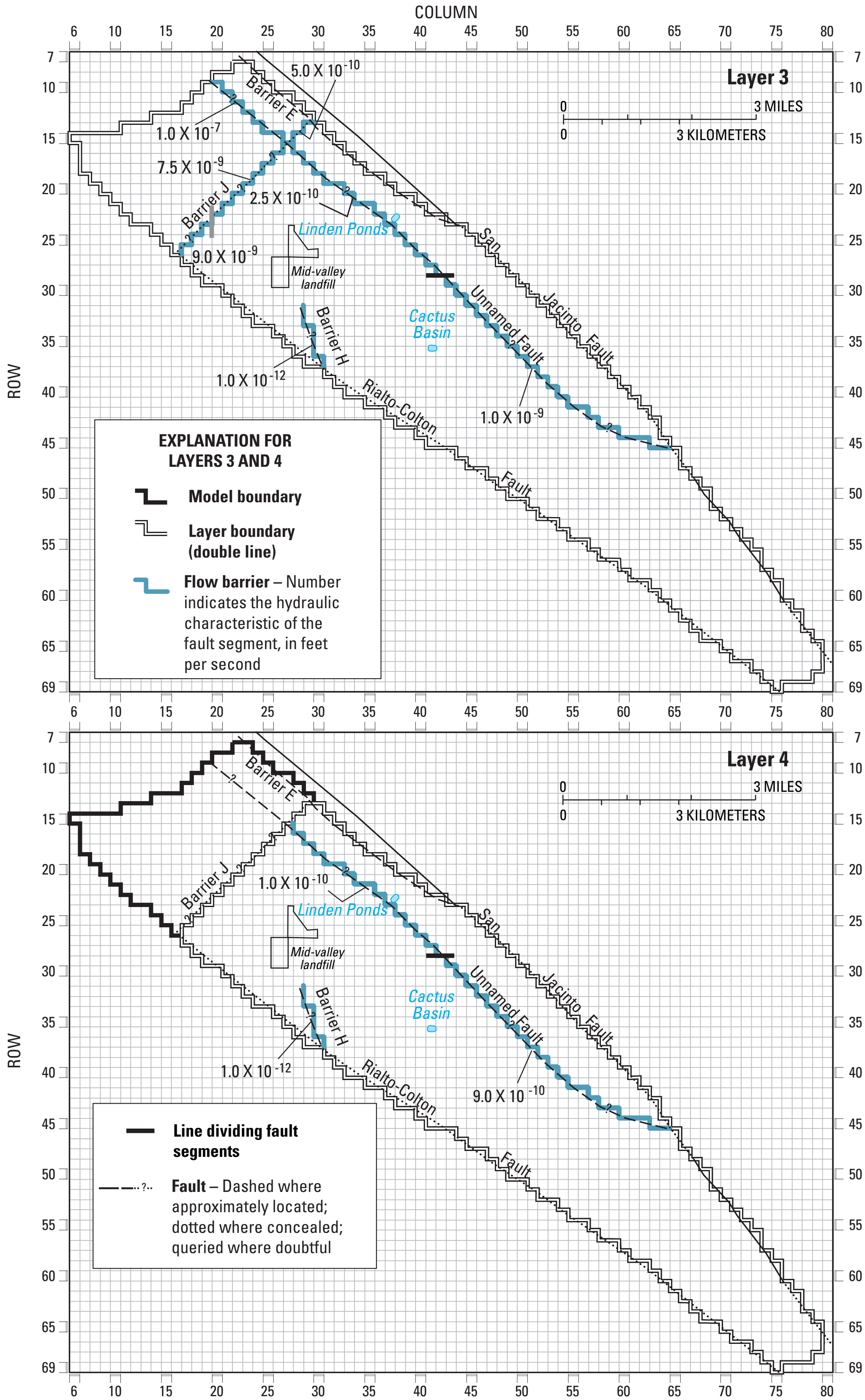


Figure 19. Model grid and areal distribution of flow barriers for model layers 3 and 4 of the Rialto–Colton Basin ground-water flow model, San Bernardino County, California.

of the unnamed fault with water southwest of the unnamed fault in layer 3 than in layer 4. Barrier H has the smallest hydraulic characteristic of any fault within the basin.

Aquifer Properties

Aquifer properties used in the model include hydraulic conductivity, aquifer thickness, vertical leakance, storage coefficient, and specific yield. Hydraulic conductivity and top and bottom altitudes of each layer were used in this model so that transmissivity (hydraulic conductivity times saturated thickness) may be recalculated at each iteration as hydraulic heads change. Recalculating the transmissivity at each iteration, along with the potential for storage-term conversions, allows simulation of changes between confined and unconfined conditions. Confined conditions may be simulated when the hydraulic head rises above a confining unit, and aquifer thickness is used to calculate transmissivity. Conversely, unconfined conditions may be simulated when hydraulic heads decline below the bottom of the confining unit, and the saturated thickness (the difference between simulated water-table surface and bottom altitude of the water-bearing unit) is used to calculate transmissivity. In this model, layer 1 is always unconfined, and layers 2 and 3 are allowed to convert back and forth from confined to unconfined conditions and allowed to rewet cells that have gone dry in the previous iterations. Layer 4 is strictly confined.

Hydraulic Conductivity

Hydraulic conductivity refers to the water-transmitting characteristic of a material in quantitative terms (Heath, 1983). Hydraulic conductivity multiplied by the saturated thickness of the aquifer equals the transmissivity (the capacity of an aquifer to transmit water of the prevailing kinematic viscosity) (Heath, 1983) and is used by MODFLOW in both the initial-condition and transient-state ground-water flow simulations.

The distribution of hydraulic conductivity for layers 1–4 is shown in figure 20. A constant value of 0.0015 ft/s (130 ft/d) was assigned to layer 1 (fig. 20*A*). This value is based on a description of river-channel deposits by Dutcher and Garrett (1963) and on hydraulic-conductivity values for geologic materials reported by Freeze and Cherry (1979).

A constant hydraulic-conductivity value of 0.0039 ft/s (337 ft/d) was assigned to layer 2 (fig. 20*B*). This value is based on hydraulic conductivities reported by Dutcher and Garrett (1963) for younger alluvium, which probably approximates the upper water-bearing unit, and hence, layer 2.

Hydraulic-conductivity values for layer 3 varied throughout the basin (fig. 20*C*). Hydraulic-conductivity values range from 0.0001547 ft/s (13 ft/d) southwest of the unnamed fault northwest of Barrier J to 0.0009259 ft/s (80 ft/d) southeast of Barrier J. The hydraulic-conductivity values southeast of Barrier J were reported by Geosciences Support Services, Inc. (1994), and are based on calculations using specific capacities, saturated thickness, and a constant (2,000, in this case) that accounts for the storage coefficient and transmissivity of the aquifer at the well, effective radius of the well, and duration of the specific-capacity test (Heath, 1983, p. 61) for selected wells in the Rialto–Colton Basin. The hydraulic-conductivity value northeast of the unnamed fault north of Barrier J (0.0001736 ft/s [15 ft/d]) is reported by Dutcher and Garrertt (1963). The value assigned to cells southwest of the unnamed fault was slightly lower (0.0001547 [13 ft/d]) to account for different aquifer materials farther west of Lytle Creek.

Hydraulic-conductivity values for layer 4 varied throughout the basin (fig. 20*D*). Hydraulic-conductivity values range from 0.0001010 ft/s (9 ft/d) to 0.0002314 ft/s (20 ft/d). No information or data were available for the hydraulic conductivity of layer 4 (lower water-bearing unit). The hydraulic-conductivity values were estimated to be one-fourth those of layer 3, which are consistent with those for the finer grained (silty sand) material (Freeze and Cherry, 1979) present in the lower water-bearing unit.

Aquifer Thickness

Aquifer thickness is the difference between the top and bottom altitudes of a water-bearing unit under confined conditions, and the water table and the bottom of the unit for unconfined conditions. Aquifer thickness is used to calculate transmissivity under confined conditions. The aquifer thickness distributions for layers 1–4 during initial conditions are shown in figure 21. Thicknesses were determined from altitudes of the water table and top and bottom altitudes, as described above, along cross sections shown in figure 7, and values between the section lines were interpolated. The

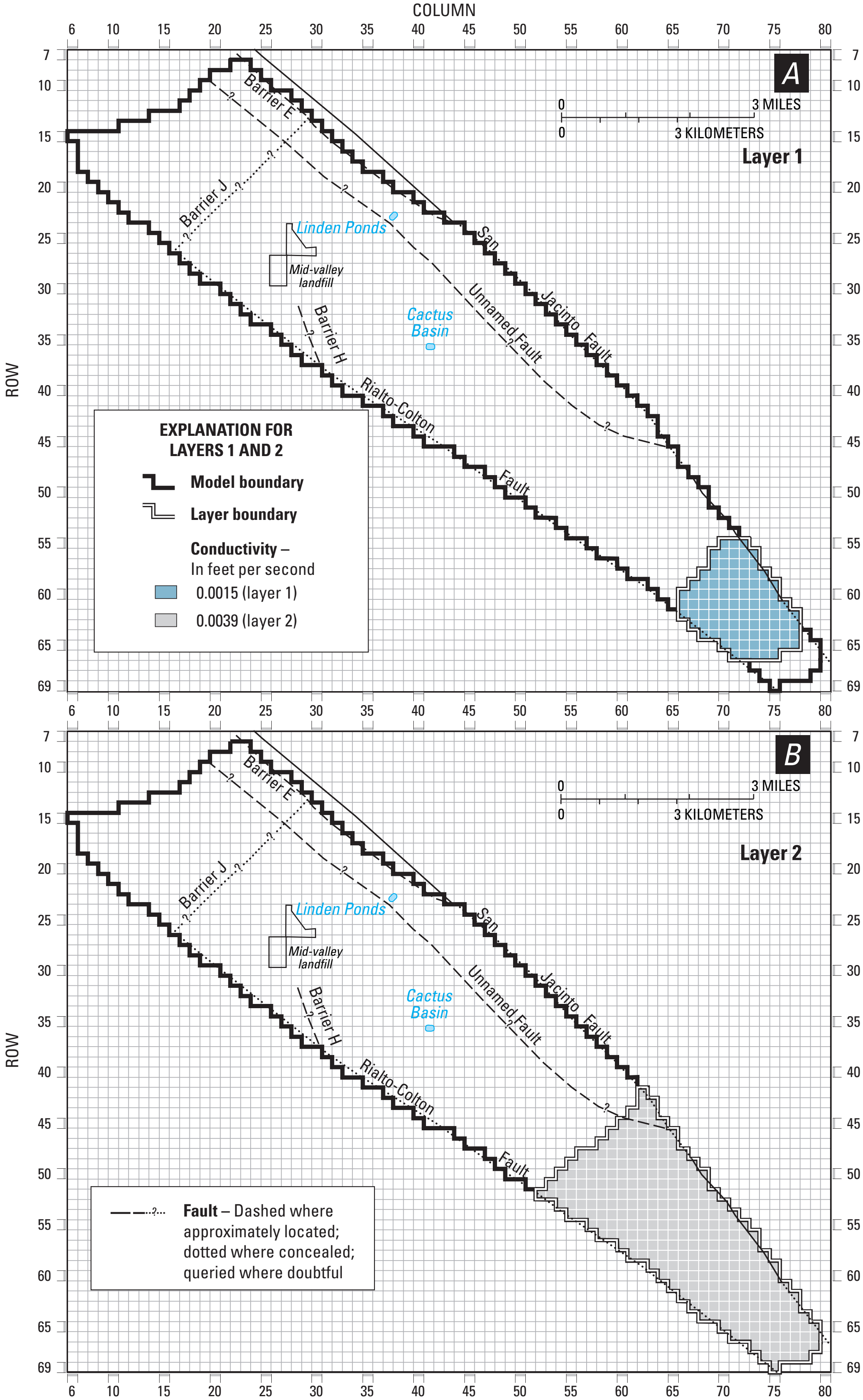
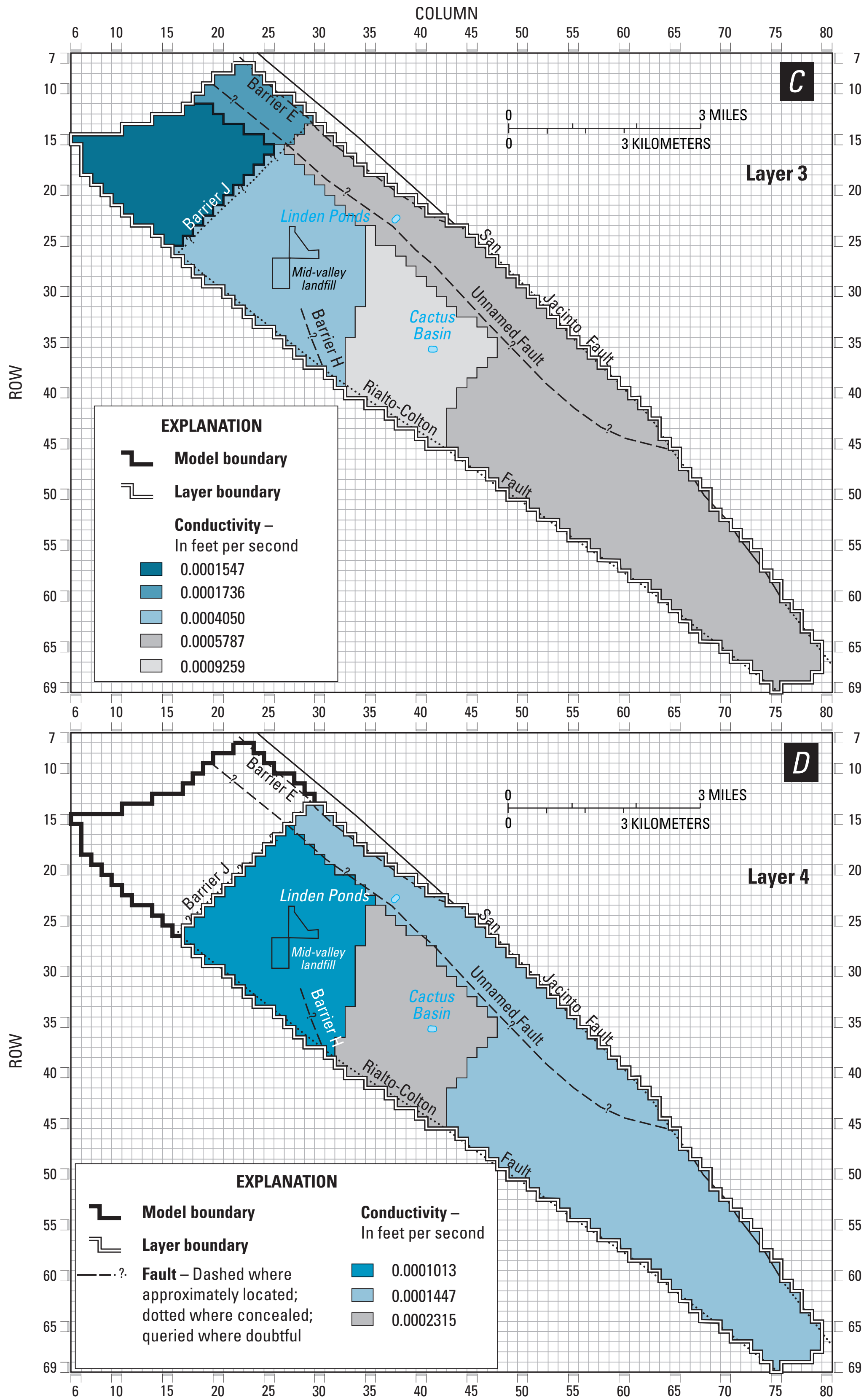


Figure 20. Model grid and areal distribution of hydraulic conductivity for layers 1–4 of the Rialto–Colton Basin ground-water flow model, San Bernardino County, California.



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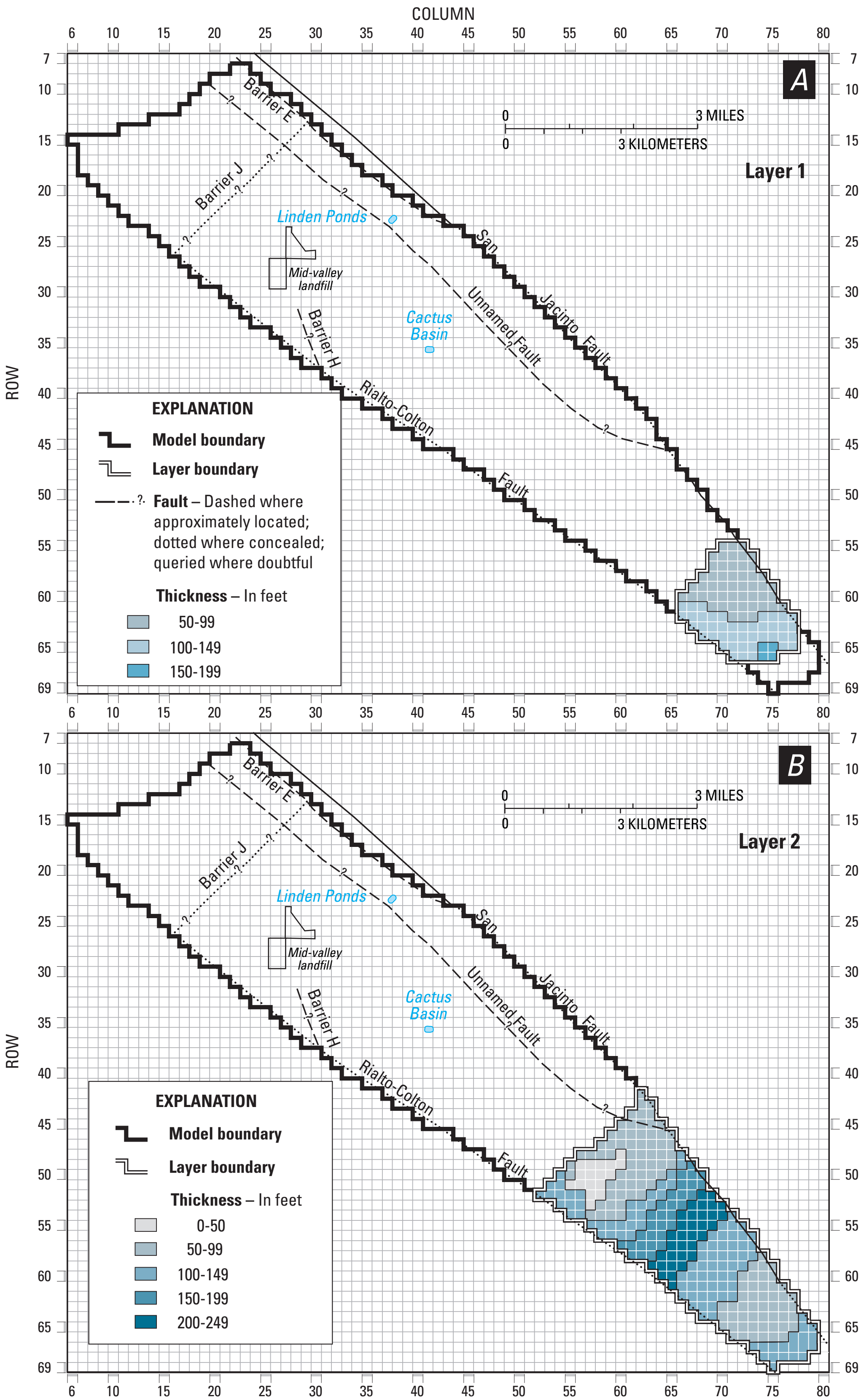


Figure 21. Model grid and areal distribution of thickness for layers 1–4 of the Rialto–Colton Basin ground-

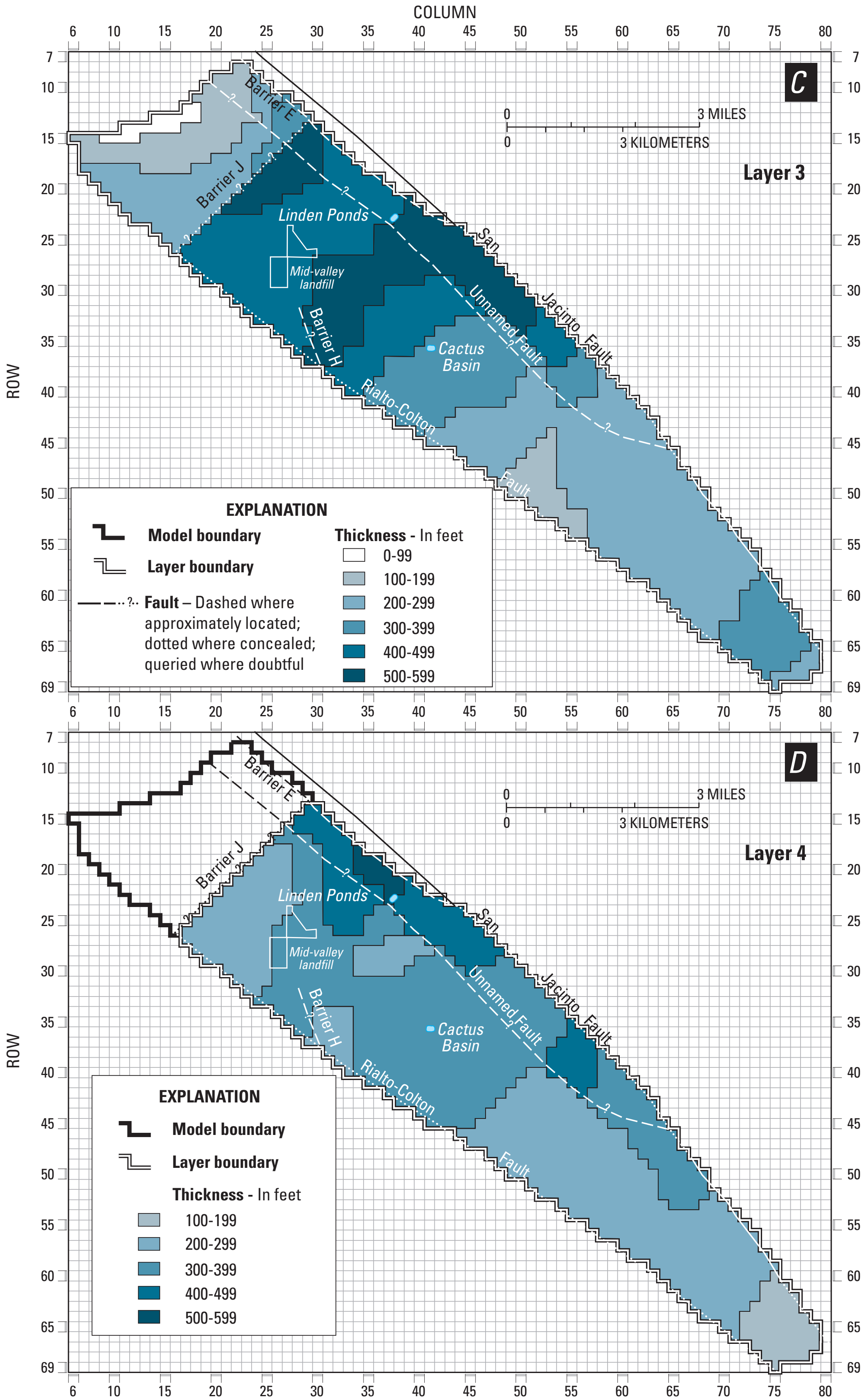


Figure 21.—Continued.

thickness of layer 1 ranges from 50 ft in the northeast to 200 ft in the southwest (fig. 21*A*). The thickness of layer 2 ranges from a feather edge to 250 ft. Layer 2 is thickest in the center of the layer and thins toward the northwest where the upper water-bearing unit becomes unsaturated. The thickness of layer 3 ranges from a feather edge to 600 ft. The thinnest part of layer 3 is north of Barrier J, and the thickest part of layer 3 is in the northwestern part of the layer south of Barrier J. Layer 3 generally thins from northwest to southeast. The thickness of layer 4 ranges from 100 to 600 ft and is greatest adjacent to the northeastern boundary.

Vertical Conductance

Vertical leakage between adjacent layers occurs whenever there is a difference in hydraulic head between layers. The rate at which leakage occurs is determined by the following equation:

$$Q = \frac{K_v * DELR_j * DELC_i (H_k - H_{k+1})}{B},$$

where:

- Q is the vertical leakage [L^3/T],
- K_v is the effective value of vertical hydraulic conductivity between the center of cell i,j,k and cell i, j, k+1 [L/T],
- $DELR_j$ is the cell width along row j [L],
- $DELC_i$ is the cell width along column i [L],
- B is the distance between the centers of model layer k and k+1 [L]
- H_k is the hydraulic head in cell i,j,k [l]
- H_{k+1} is the hydraulic head in cell i,j,k+1 [L]
- *cell i,j,k* represents a model cell in row i, column j, and layer k [dimensionless], and
- *cell i,j,k+1* represents a model cell in row i, column j, and layer k+1 [dimensionless].

The quantity of K_v/B in the above equation is referred to the "vertical leakance term" and is designated "Vcont" in this report. The ground-water flow model requires that the user specify the term Vcont as input data. Vcont is calculated using the following equation (McDonald and Harbaugh, 1988, p. 5–13):

$$Vcont_{i,j,k+1/2} = \frac{1}{\frac{delv_k/2}{kz_{i,j,k}} + \frac{delv_{k+1}/2}{kz_{i,j,k+1}}},$$

where:

- $delv_k$ is the thickness of model layer k,
- $delv_{k+1}$ is the thickness of model layer k+1,
- $kz_{i,j,k}$ is the vertical hydraulic conductivity of the upper layer in cell i,j,k, and
- $kz_{i,j,k+1}$ is the vertical hydraulic conductivity of the lower layer in cell i,j,k+1.

The value of vertical hydraulic conductivity, kz, is typically one-tenth to one-hundredth of the horizontal hydraulic conductivity. In this model, the vertical hydraulic conductivity of layers 1, 2, and 3 is one-tenth of the horizontal conductivity, and the conductivity of layer 4 is one-hundredth of the horizontal conductivity. The calculated Vcont distributions between model layers 1 and 2, 2 and 3, and 3 and 4 are presented in figure 22.

Storage Coefficient and Specific Yield

The storage coefficient is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head and is dimensionless (Heath, 1983, p. 28). The value of the storage coefficient depends on whether the aquifer is confined or unconfined. The storage coefficient for most confined aquifers ranges from about 0.00001 to 0.001. The storage coefficient for unconfined aquifers, which is virtually equal to the specific yield, usually ranges from about 0.1 to 0.3 (Heath, 1983, p. 28-9). The primary storage coefficient is used to simulate confined conditions, and the secondary storage coefficient is used to simulate unconfined conditions in a layer that can convert from confined to unconfined. The storage-coefficient values were determined from model calibration as described in the "Transient Simulation" section. Layer 1 is simulated as always unconfined, and the value of the primary and secondary storage coefficient is 0.30 (fig. 23*A*).

Layer 2 is simulated as always unconfined where it is the uppermost layer, and the primary and secondary storage coefficient is 0.30 (fig. 23*B*). Where layer 2 underlies layer 1, the storage-term conversion is allowed to occur. The primary storage coefficient is 0.0001 and the secondary storage coefficient is 0.30 (fig. 23*B*).

The distribution of storage coefficients for layer 3 is variable (fig. 23*C*). Layer 3 is the only layer active northwest of Barrier J. Unconfined conditions are assumed at all times in this area, and the primary and

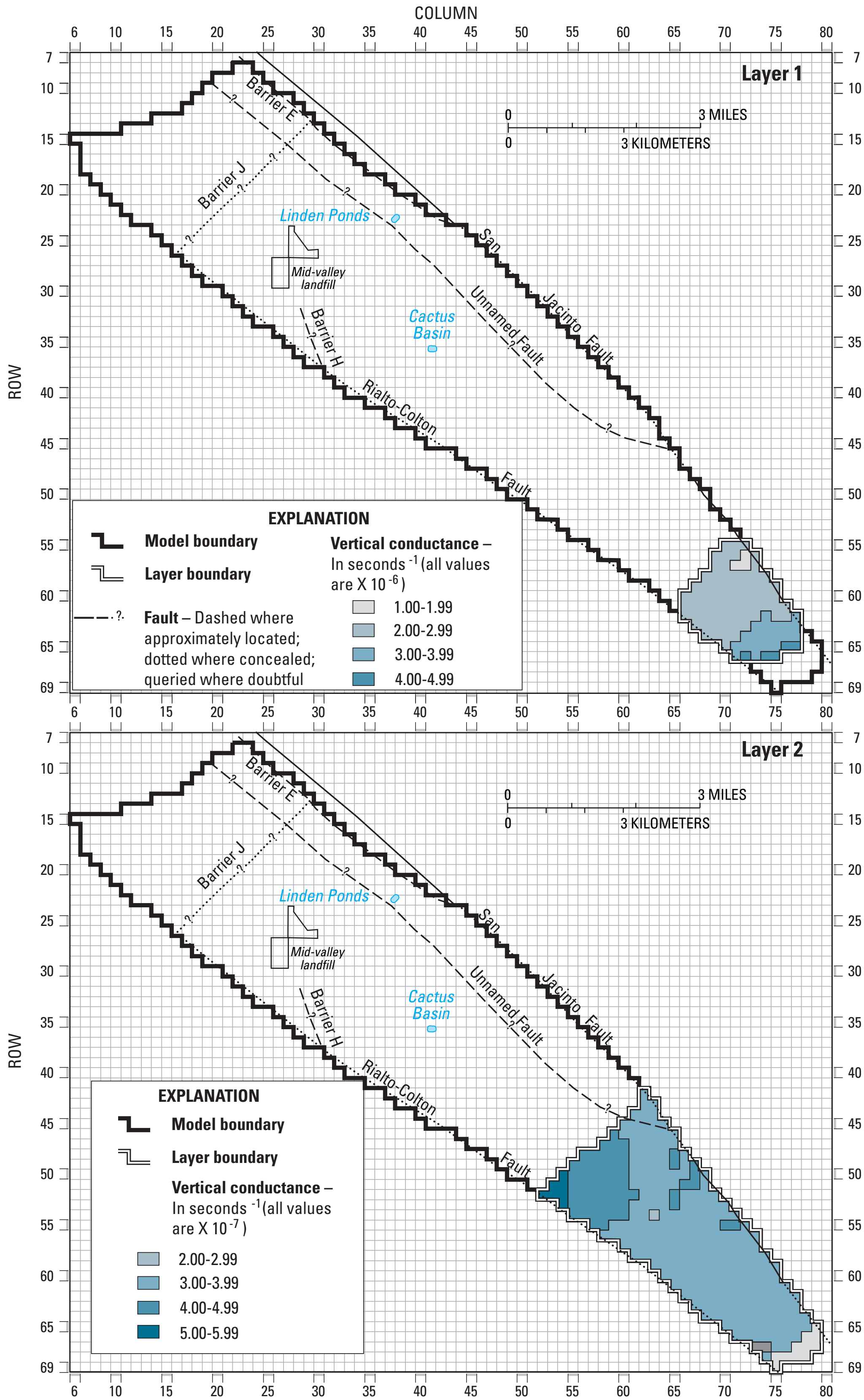


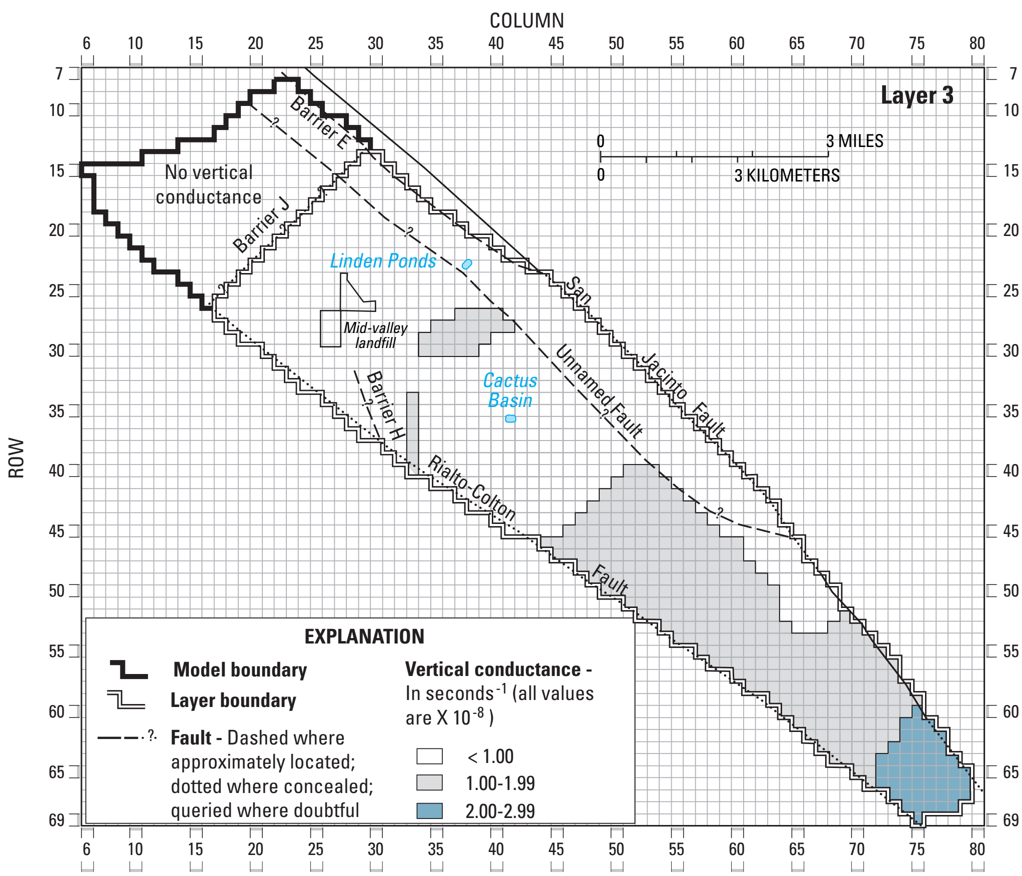
Figure 22. Model grid and real distribution of vertical conductance between layers 1 and 2, 2 and 3, and 3

secondary storage coefficient is 0.25. Southeast of Barrier J, the primary and secondary storage coefficients varied according to degree of aquifer confinement. Immediately southeast of Barrier J and southwest of the unnamed fault, layer 3 is always confined and the primary and secondary storage coefficients are 0.0001 (fig. 23*C*). Between this area and where layer 3 underlies layer 2, the primary storage coefficient is 0.0001 and the secondary coefficient is 0.075 (fig. 23*C*). Where layer 3 underlies layer 2, the primary storage coefficient is 0.005 and the secondary coefficient is 0.05. Secondary storage coefficients of 0.075 and 0.05 indicate partially confined conditions owing to the existence of discontinuous clay lenses in these areas. Northeast of the unnamed fault, the primary storage coefficient is 0.0001 except near te junction of the unnamed frult and the San Jacinto Fault where it is 0.005; the secondary storage coefficient is 0.15 in the northernmost part and 0.05 in the southernmost part (fig. 23*C*).

The distribution of primary and secondary storage coefficient for layer 4 is shown in figure 23*D*. It is assumed that the head in layer 4 will never decline below the bottom altitude of layer 3, and these confined conditions prevail all the time. The primary and secondary storage coefficient for layer 4 is 0.0001.

Model Calibration

Ground-water conditions during the period 1945–96 were used to calibrate the flow model to transient or time-dependent conditions. Ground-water conditions were adjusted until simulated water levels approximated measured water levels. Seepage data for the Santa Ana River and (or) Warm Creek were not available for calibration. A transient condition exists when aquifer recharge and discharge change with time, resulting in an increase or decrease in the quantity of water stored in the basin. Ground-water conditions in



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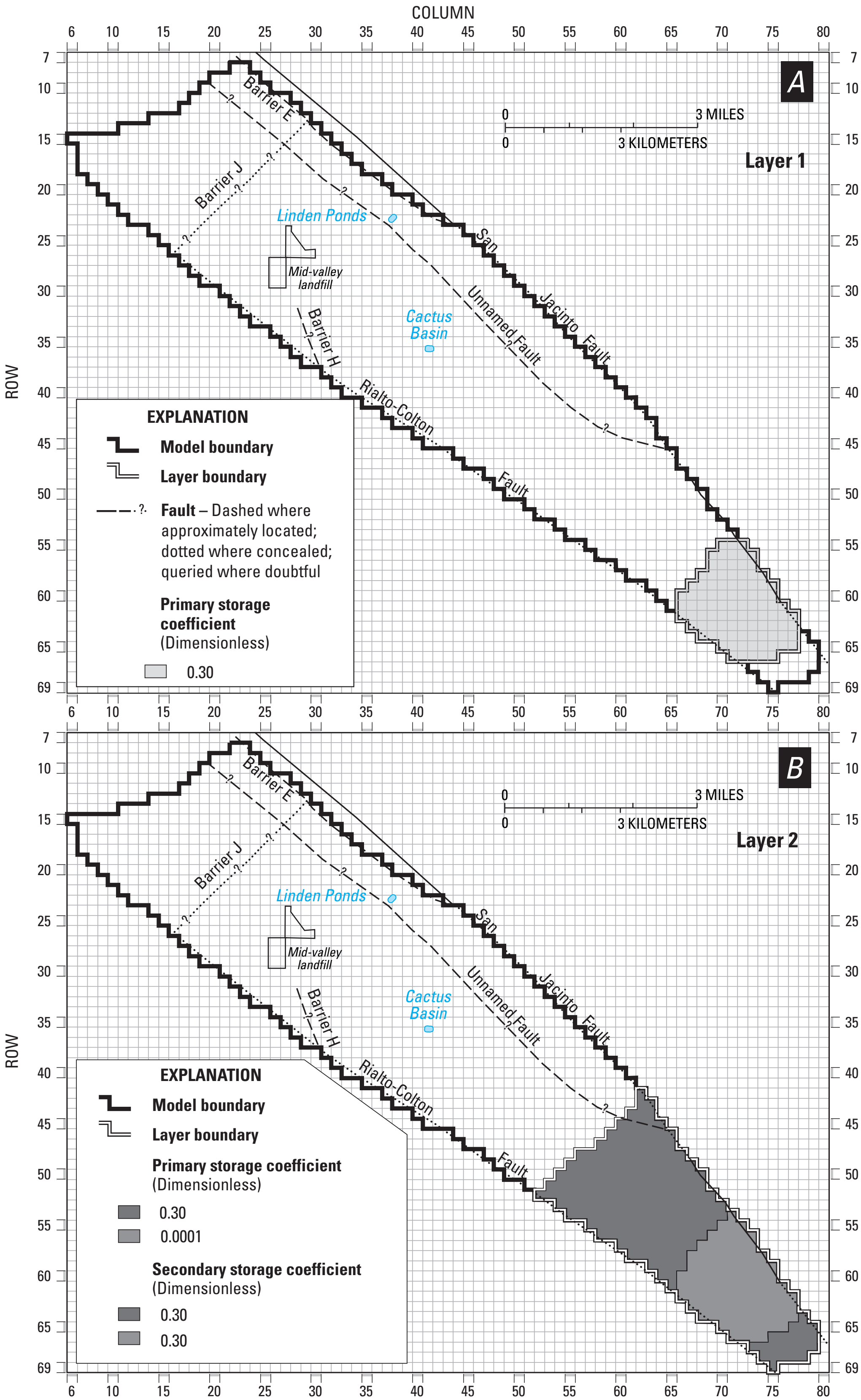


Figure 23. Model grid and areal distribution of primary and secondary storage coefficients for layers 1–4 of

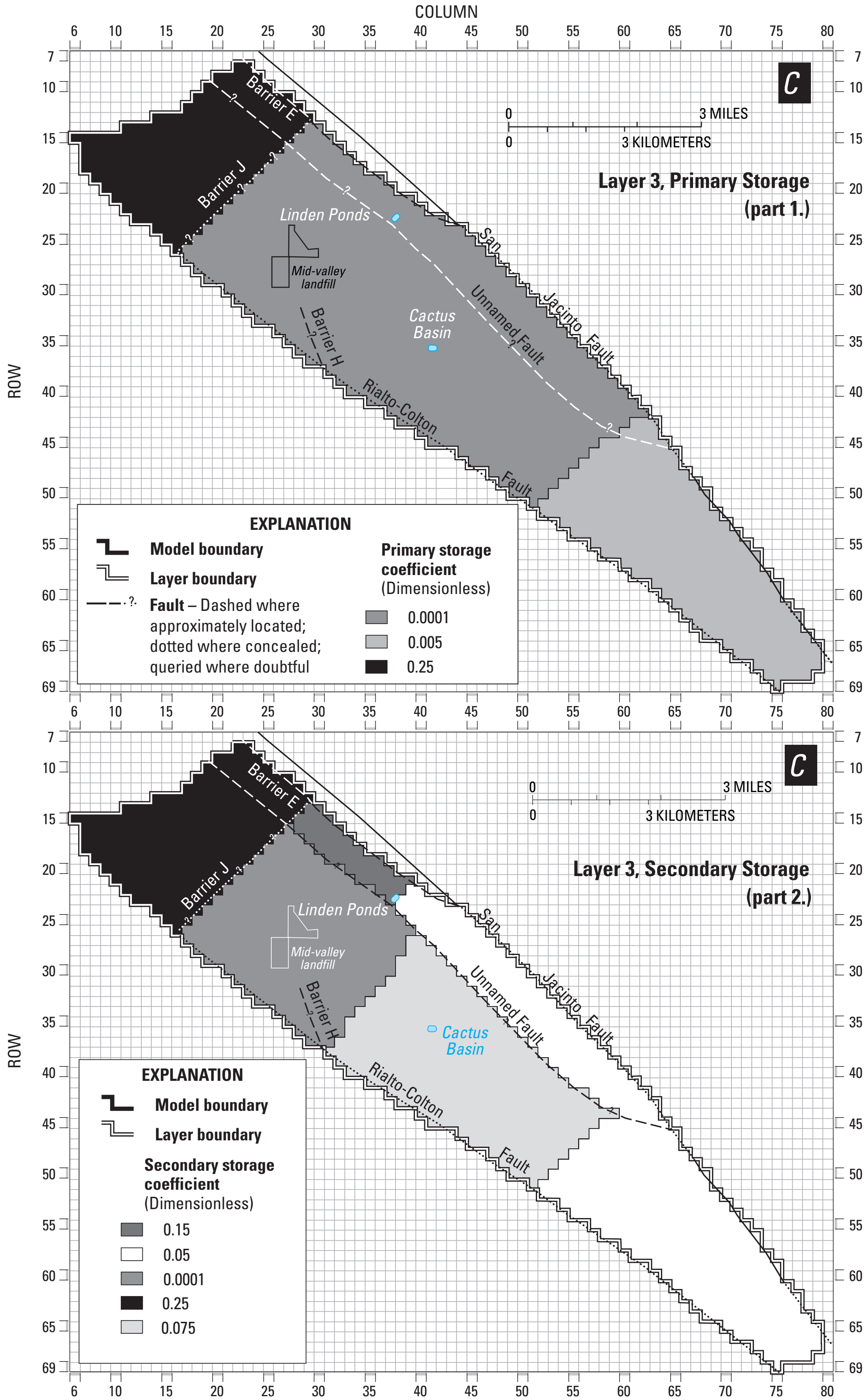


Figure 23.—Continued.

1945 were used to provide initial conditions for the transient simulation. This year was chosen for consistency with an existing ground-water flow model in the adjacent Bunker Hill Basin (W.R. Danskin, USGS, oral commun., 1994) and because conditions at that time approximated steady state, whereby net recharge to the system equaled net discharge from the system, water levels remained relatively constant, and aquifer storage did not change with time.

Initial Conditions

A set of initial conditions is required input for transient calibration. Hydraulic heads generated by simulating initial conditions primarily are dependent on the recharge and discharge from the ground-water system, the hydraulic conductivity and layer thicknesses of the aquifer system, and vertical leakance between layers. The initial-conditions simulation consisted of trial-and-error modification of (1) the initial estimates of hydraulic conductivity, (2) the quantity and distribution of underflow from the Lytle Basin to the Rialto–Colton Basin, (3) the distribution of underflow from the Bunker Hill Basin to the Rialto–Colton Basin, (4) the conductance of the general-head boundary between the Rialto–Colton Basin and the Chino and North Riverside Basins, and (5) the horizontal-flow-barrier hydraulic characteristic assigned to duplicate measured basinwide hydraulic heads. Ground-water conditions for 1945 were used to simulate initial conditions in the Rialto–Colton Basin. Conditions during 1945 approximated steady state, whereby net recharge to the system equaled net discharge from the system and, because hydraulic heads are constant in simulating initial conditions, the storage component of the system is not part of the initial-condition simulation.

Values for underflow from the Lytle Basin to the Rialto–Colton Basin were calculated to be equivalent to 35 percent of discharge in Lytle Creek in 1945 (discharge in Lytle Creek, 31,300 acre-ft; underflow about

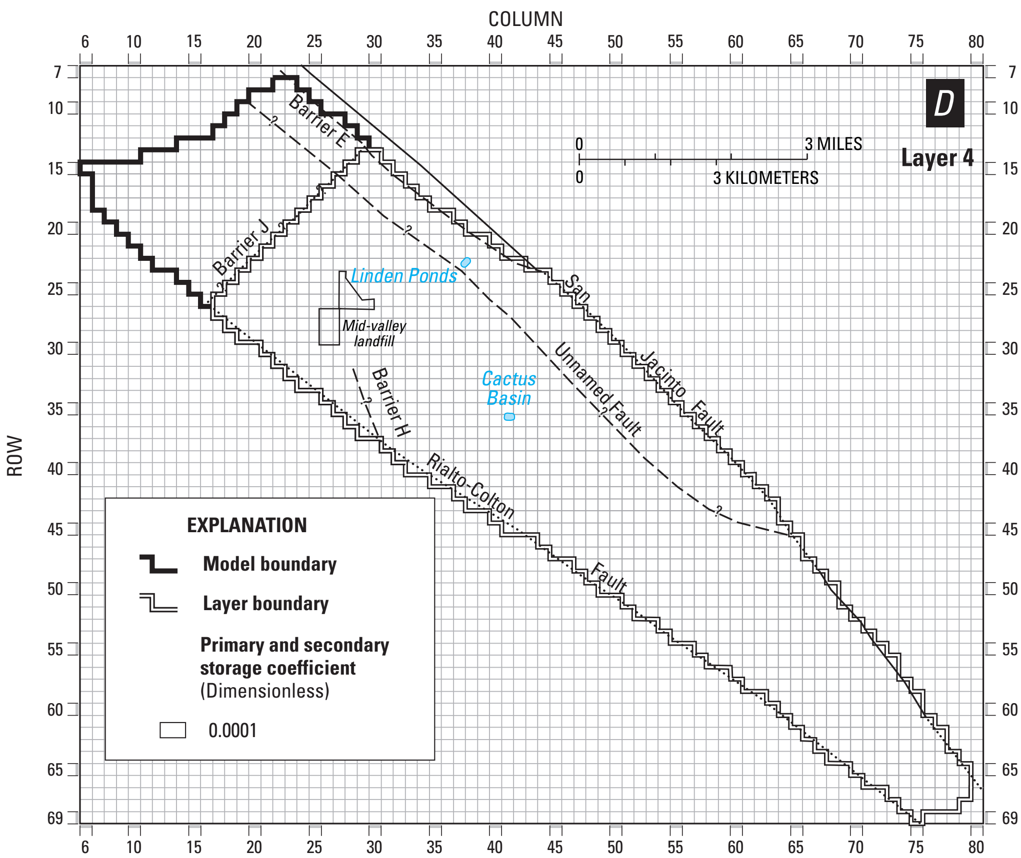


Figure 23.—Continued.

10,960 acre-ft). Fifty percent of this underflow (about 5,480 acre-ft) occurs northwest of Barrier J, and fifty percent southeast of Barrier J. Underflow from the Bunker Hill Basin to the Rialto–Colton Basin for 1945 was estimated to be about 13,660 acre-ft. Ungaged runoff and subsurface inflow for 1945 was estimated to be 2,930 acre-ft from the San Gabriel Mountains and 90 acre-ft from the Badlands. Seepage loss from the Santa Ana River and Warm Creek was computed by the flow model to be about 3,260 acre-ft. Streambed-conductance estimates for the adjacent Bunker Hill ground-water flow model (0.1 ft^2/s) were used in this simulation. The quantity of irrigation return flow for 1945 was estimated to be about 2,040 acre-ft (30 percent of total pumpage). Average annual recharge from precipitation was 860 acre-ft. The quantity of underflow from the Rialto–Colton Basin to the Chino and North Riverside Basins (about 24,710 acre-ft) was computed by the flow model. Water levels measured in wells 1S/4W-29H2 and 1S/4W-28L1 in 1945 were used as external heads in the general-head-boundary package, which simulates underflow between the Rialto–Colton Basin and the Chino and North Riverside Basins. Discharge from pumpage for 1945 was assumed to be the same as for 1947 (6,791 acre-ft) when collection of pumpage data began. Net pumpage used in the initial-conditions simulation was 4,754 acre-ft (70 percent of total pumpage).

Transient Simulation

Ground-water conditions (stresses) during the period 1945–96 were used as input to calibrate the ground-water flow model to transient or time-dependent conditions. Transient conditions in the Rialto–Colton Basin are the result of stresses on the system imposed by the major sources of recharge to and discharge from the Rialto–Colton Basin. Hydraulic heads resulting from the initial-conditions simulation were used as initial conditions for the transient simulation. The period 1945–96 was modeled as 52 one-year stress periods. Water levels in the transient period have declined and recovered in response to increases and decreases in pumpage and recharge during wet and dry periods (Woolfenden and Kadhim, 1997).

Changes in hydraulic head are dependent on recharge and discharge, boundary conditions, and aquifer properties. For transient calibration, the quantity of recharge from rainfall, the irrigation-return-flow factor, the evapotranspiration rate, and the streambed conductance are the same as those in the initial-condition calibration and were not adjusted. Annual estimates of ungaged runoff, described previously in the “Ungaged Runoff and Subsurface Inflow” section, were used in the model without modification. Annual net pumpage data, described previously in the “Pumpage” section, are measured values and were not adjusted during transient calibration except in distribution to layers as noted earlier. Therefore, the calibration procedure for transient conditions consisted of modifying (1) initial estimates of storage coefficient, (2) hydraulic conductivity, (3) bottom altitude of layer 3, (4) hydraulic conductance of the general-head boundary representing the interface between the Rialto–Colton Basin and the Chino and North Riverside Basins, (5) the hydraulic characteristic of horizontal flow barriers, (6) the quantity and distribution of underflow from the Lytle Basin to the Rialto–Colton Basin, and (7) the layer distribution of underflow from the Bunker Hill Basin to the Rialto–Colton Basin. These parameters were modified during the transient calibration until simulated hydraulic heads reasonably matched measured values. The vertical-leakance values were recalculated whenever the hydraulic-conductivity values and (or) bottom altitude of layer 3 were changed. Modifications to hydraulic conductivity, bottom altitude of layer 3, vertical leakance, hydraulic conductance of the general-head boundary, hydraulic characteristic of horizontal-flow barriers, and underflow during transient calibration were reentered into the initial-conditions model to ensure that simulated heads were not adversely affected, thus making model calibration for the Rialto–Colton ground-water flow model an iterative process.

The final values of general-head boundary conductance used in the flow model were determined by calibration. The model-calibrated values of conductance are 0.05 ft^2/s for layer 1 and 0.04 ft^2/s for layers 2 and 3.

Hydraulic conductivity in layers 1 and 2 was not adjusted during model calibration. Hydraulic-conductivity distributions in layer 3 and, consequently, layer 4 (as described in the “Hydraulic Conductivity” section, layer 4 values were estimated to be one-fourth those for layer 3) were adjusted, but it was found that water levels were relatively insensitive to this parameter. Therefore, the original parameters described in the “Hydraulic Conductivity” section were used in subsequent modeling.

Top and bottom altitudes for layers 1 and 2, bottom altitudes for layer 4, and top altitudes for layer 3 were not adjusted significantly during model calibration. Bottom altitudes for layer 3 in the northwestern part of the basin southeast of Barrier J and in the vicinity of the Linden Ponds artificial-recharge site were decreased 50 to 400 ft to produce more realistic (consistent with historical data [Dutcher and Garrett, 1963]) values and to eliminate the drying of cells in layer 3 in that area.

Primary and secondary storage-coefficient distributions for layers 1–4 are shown in figure 23. The original storage-coefficient values are based on those given by Heath (1983) for confined and unconfined aquifers. Decreasing the primary and secondary storage coefficients during transient model calibration resulted in greater short-term variation in water levels, and increasing the parameter resulted in less variation. Primary and secondary storage coefficients for all layers are a result of transient model calibration.

Calibration Results

Ground-water-level measurements made during 1945 were used for comparison with the initial-conditions simulation to determine if there was a reasonable match, and thus reasonable starting heads, for the transient simulation. Depth-dependent water-level data generally are not available for 1945; hence, composite water-level measurements made in production wells (usually perforated in more than one layer) were used for comparison during the calibration. Hydraulic heads calculated for layer 3 were compared with the available 1945 measured water levels. Layer 3 was chosen because it simulates the main water-producing unit (the middle water-bearing unit), and water levels measured in wells perforated in the different layers generally do not vary significantly (Woolfenden and Kadhim, 1997). Simulated heads and measured water levels are given in table 10. The relation between simulated head and measured water levels, shown in figure 24, indicates that, overall, the simulated heads match measured water levels well; the goodness-of-fit value is 0.99. The largest differences between simulated head and measured water level (–55.6 ft for well 1S/5W-5A2 and –40.5 ft for well 1S/5W-5A3) (fig. 25) occurred between Barrier H and the Rialto–Colton Fault. Simulated heads near the Santa Ana River and Warm Creek, and simulated heads northwest of Barrier J, generally are within 30 ft of measured water levels and five are within 20 ft (fig. 25). The maximum difference between simulated heads and measured water levels near the Santa Ana River and Warm Creek is 26.8 ft at well 1S/4W-21N1; the minimum difference is 7.7 ft at well 1S/4W-21R1. The maximum difference between simulated head and measured water level in the central part of the basin is 25.8 ft at well 1S/4W-17M1 and the minimum is –1.9 ft at well 1S/5W-12L1. Northwest of Barrier J, differences between simulated head and measured water level are 26.2 ft at well 1N/5W-17K1 and 24.4 ft at well 1N/5W-19A1.

For this report, simulated heads were compared with measured long-term changes in hydrographs of composite water levels in selected wells, and with measured short-term changes in hydrographs of water lev-

Table 10. Measured water-level altitude and simulated hydraulic head in selected wells for initial conditions (1945) in the Rialto–Colton Basin, San Bernardino County, California

[Water-level altitude and hydraulic head in feet above sea level]

State well number	Measured water-level altitude	Simulated hydraulic head	Residual
1N/5W-17K1	1,809.4	1,835.6	26.2
1N/5W-19A1	1,658.3	1,682.7	24.4
1N/5W-28J1	1,083.1	1,105.9	22.8
1S/5W-5A2	1,202.9	1,147.3	–55.6
1S/5W-5A3	1,187.8	1,147.3	–40.5
1S/5W-3A1	1,061.5	1,073.6	12.1
1S/5W-2C1	1,056.6	1,067.2	10.6
1S/5W-2K1	1,048.5	1,055.5	7.0
1S/5W-12L1	993.8	991.9	–1.9
1S/5W-12N1	999.9	992.4	–7.5
1S/4W-7C1	1,043.2	1,051.4	8.2
1S/4W-18E1	943.1	958.1	15.0
1S/4W-18B2	944.0	966.7	22.7
1S/4W-17M1	934.8	960.6	25.8
1S/4W-21N1	929.8	956.6	26.8
1S/4W-21L1	941.9	962.6	20.7
1S/4W-21P1	947.1	960.1	13.0
1S/4W-21Q1	942.0	958.3	16.3
1S/4W-21Q3	936.0	960.0	24.0
1S/4W-21R1	955.3	963.0	7.7
1S/4W-28H1	936.2	955.6	19.4
1S/4W-28K2	931.5	948.8	17.3
1S/4W-27N1	937.6	957.9	20.3

els in multiple-depth observation wells (cluster wells) installed for this project. Model-simulated hydraulic heads were compared with measured long-term composite water levels at 20 production wells for 1945–96 (fig. 26). The model generally simulated heads well northwest of Barrier J and during 1945–82 in the central part of the basin (for example, wells 1S/5W-2K1, 1S/5W-12L1, and 1S/4W-18F1).

Hydrographs for wells northwest of Barrier J (1N/5W-17K1 and 1N/5W-19A1) and in the central part of the basin during 1945–82 show the smallest difference between simulated heads and measured water levels (fig. 26). Simulated heads and measured water levels in the central part of the basin generally are within 10 ft until about 1982–85 when differences become greater (for example, wells 1S/5W-2K1 and 1S/5W-12L1) (fig. 26). Prior to 1982, simulated heads generally were within the range of measured water-level fluctuation at wells 1S/5W-2K1, 1S/5W-3A1, and 1S/5W-12L1. After 1982–85, simulated heads were as much as 50 ft below measured water levels at well 1S/5W-2K1 and as much as 25 ft below measured water levels at well 1S/5W-12L1. Simulated heads generally were about 10 to 50 ft higher than measured water levels in well 1S/4W-18F1.

In the northwestern part of the basin southeast of Barrier J, simulated heads in wells 1N/5W-34M1, 1N/5W-27D1, and 1N/5W-34B1 were as much as 50 feet higher than measured water levels during 1945–82 but matched measured water levels well after 1982. In the compartment between Barrier H and the Rialto–Colton Fault, simulated heads match well during 1945–82 but are comparatively low during 1982–96. Near the Santa Ana River and Warm Creek, simulated heads generally rose above measured water levels during the periods—except during 1965–72

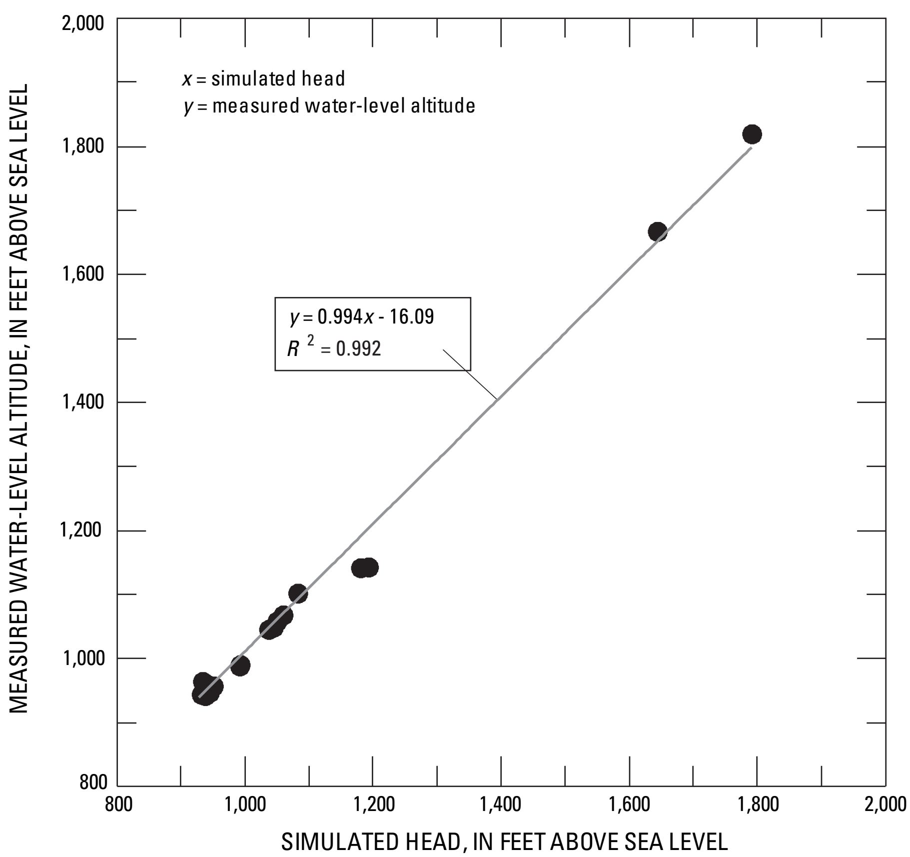


Figure 24. Relation between simulated head and measured water-level altitude, 1945, in the Rialto–Colton Basin, San Bernardino County, California.

when simulated heads compared well with measured water levels (for example, 1S/4W-21N1and 1S/4W-21Q3) (fig. 26). Simulated heads rose above measured water levels during the period 1945–65 when data were available in wells 1S/4W-21K1, 1S/4W-21K2, 1S/4W-21Q3, and 1S/4W-28H1 (fig. 26). The differences between simulated heads and measured water levels, particularly in the northwestern part of the basin, may be due, in part, to unknown fault geometry and geologic structure.

Model-simulated heads were compared with recent measured depth-dependent water levels in 29 wells for 1992–96 (fig. 27). The simulated heads and measured water levels for layers 1 and 2 are shown in the hydrographs for wells 1S/4W-20H5 and

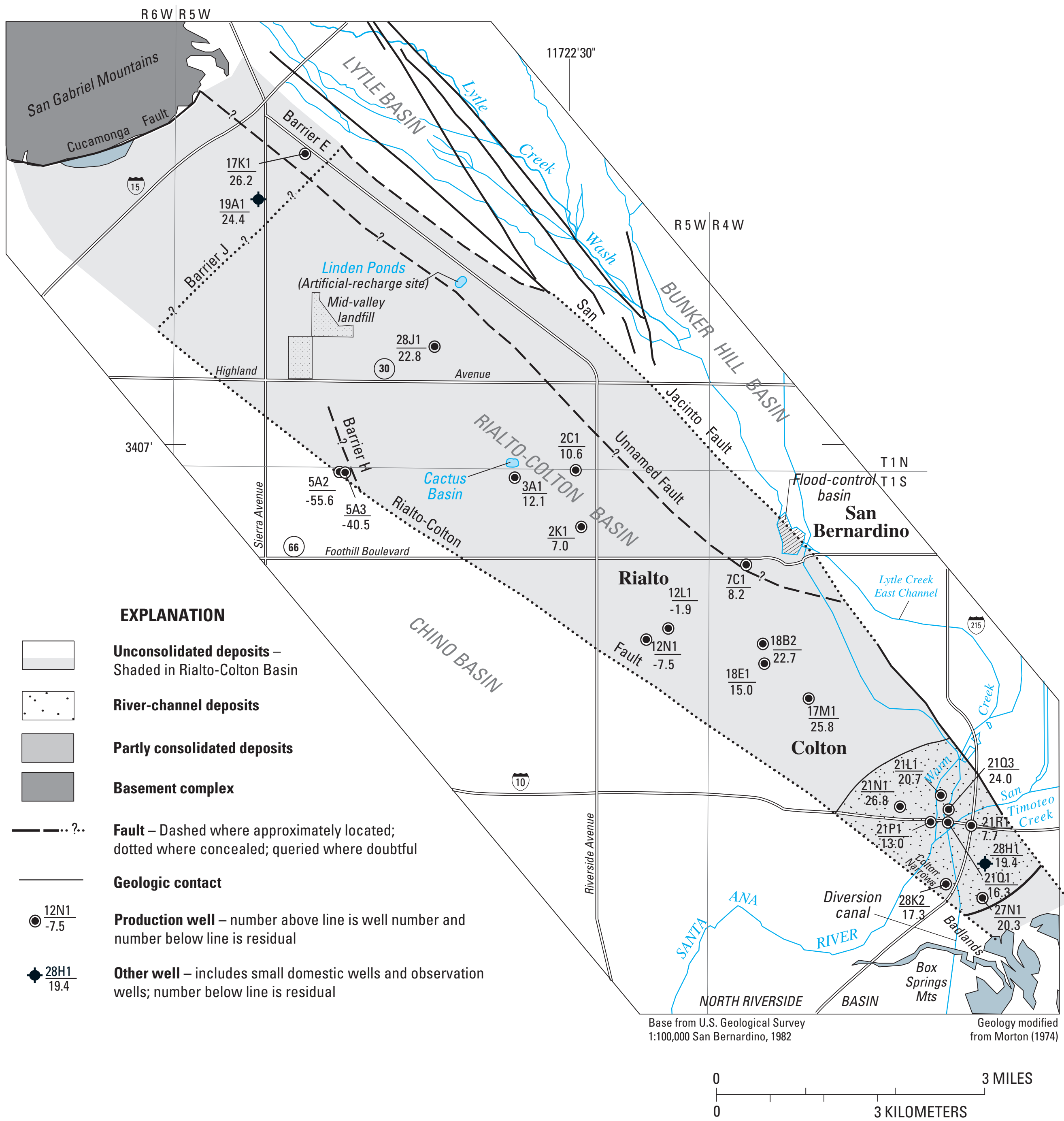


Figure 25. Distribution of residuals for the initial-conditions (1945) simulation in the Rialto–Colton Basin, San Bernardino County, California.

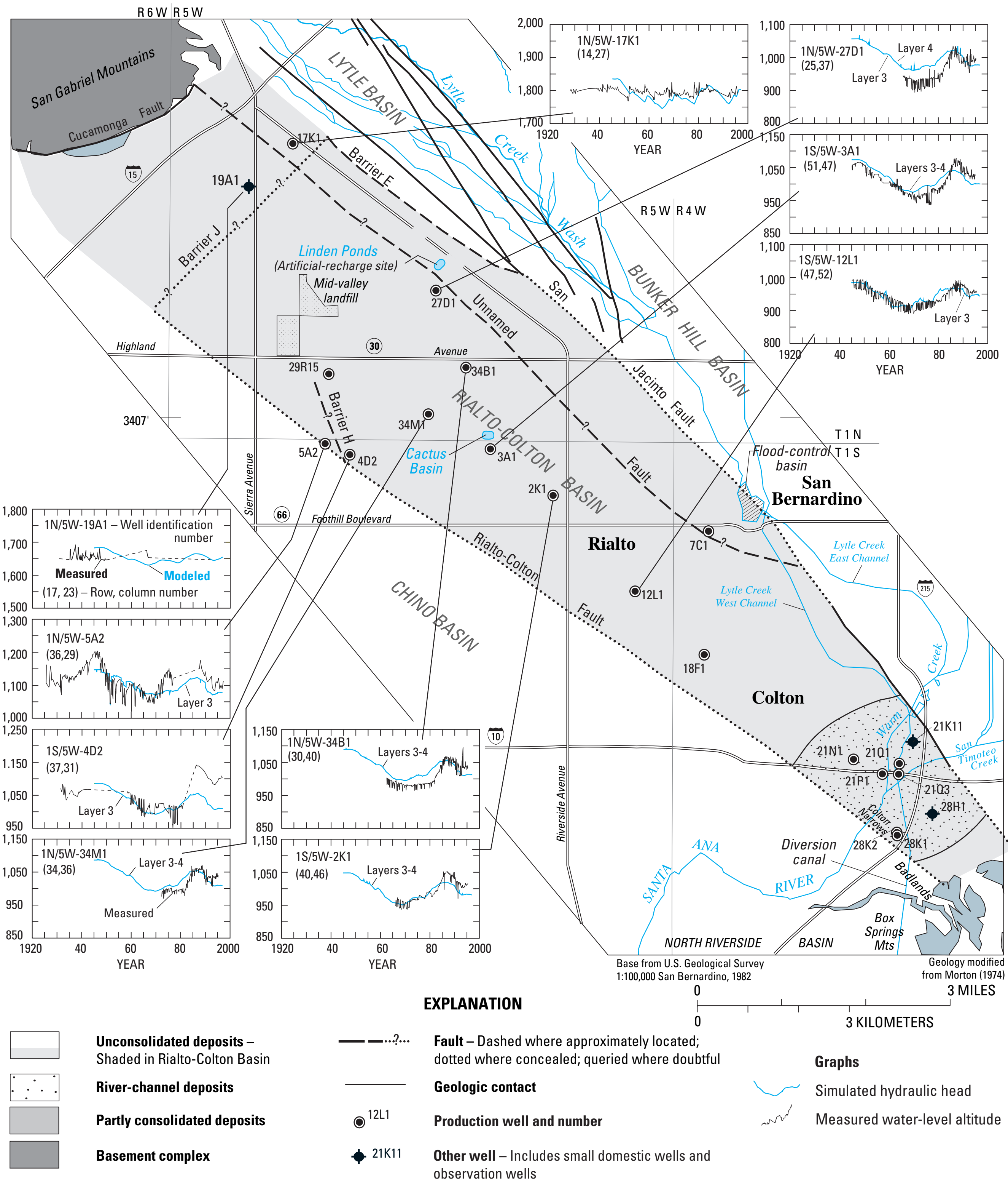
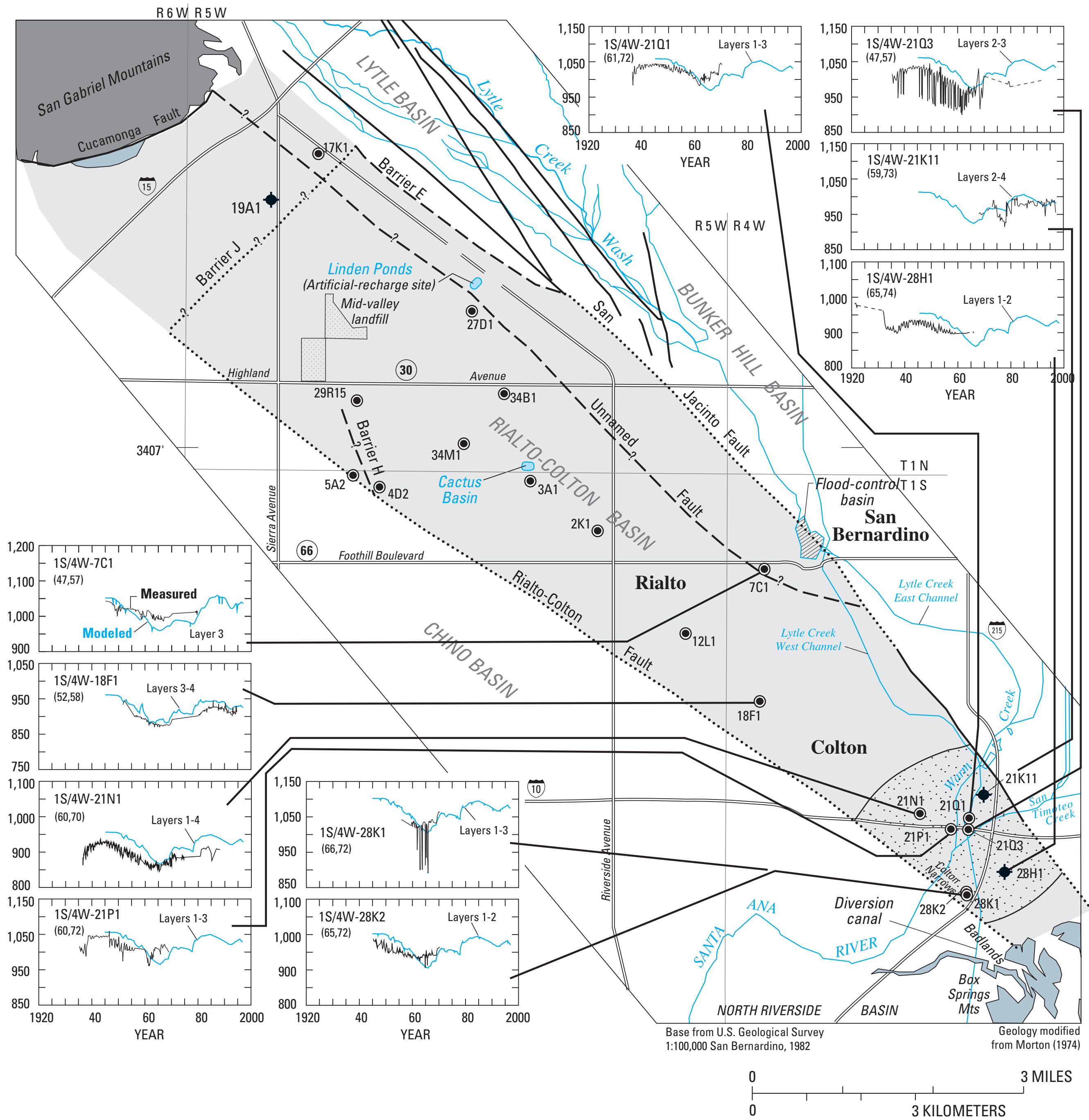


Figure 26. Location of wells, and hydrographs showing simulated heads and measured water-level altitudes (in feet above sea level) for selected production wells in the Rialto–Colton Basin, San Bernardino County, California.

1S/4W-20H4, respectively. Simulated heads generally are within 25 ft of measured water levels in both wells.

Simulated heads in layer 3 in the compartment between the unnamed fault and the San Jacinto Fault (wells 1N/5W-21K3, 1N/5W-22N3, and 1N/5W-35B4) generally were within 50 ft of measured water levels. Simulated heads in wells at the artificial-recharge ponds (1N/5W-22N3-5) and wells upgradient from the ponds (1N/5W-21K3) respond sooner to both artificial and natural recharge than do measured water levels (fig. 27). This difference may be due to the time lag between when surface spreading of imported water occurs and when the imported water actually recharges the water table during initial wetting. Artificial recharge and



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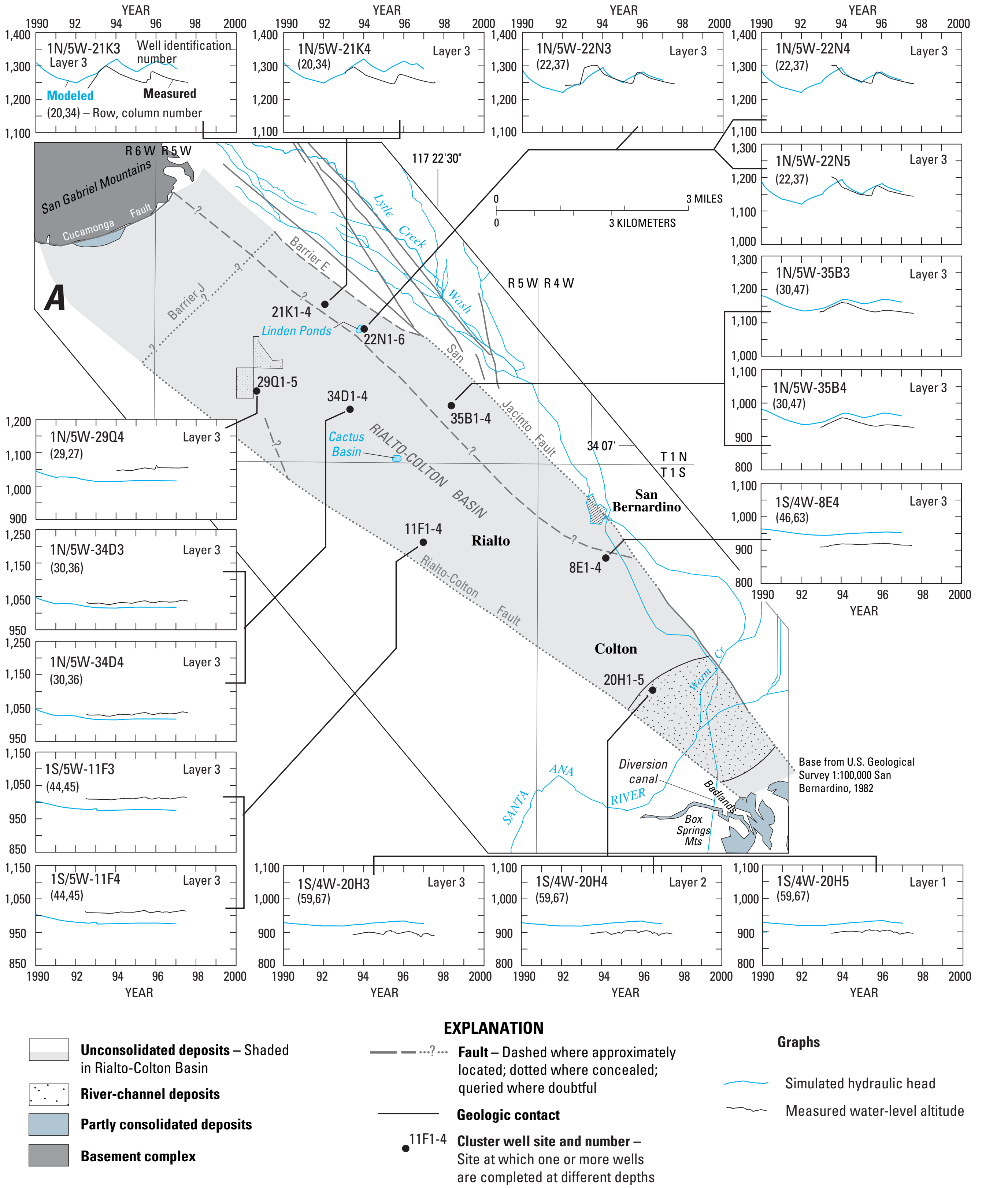
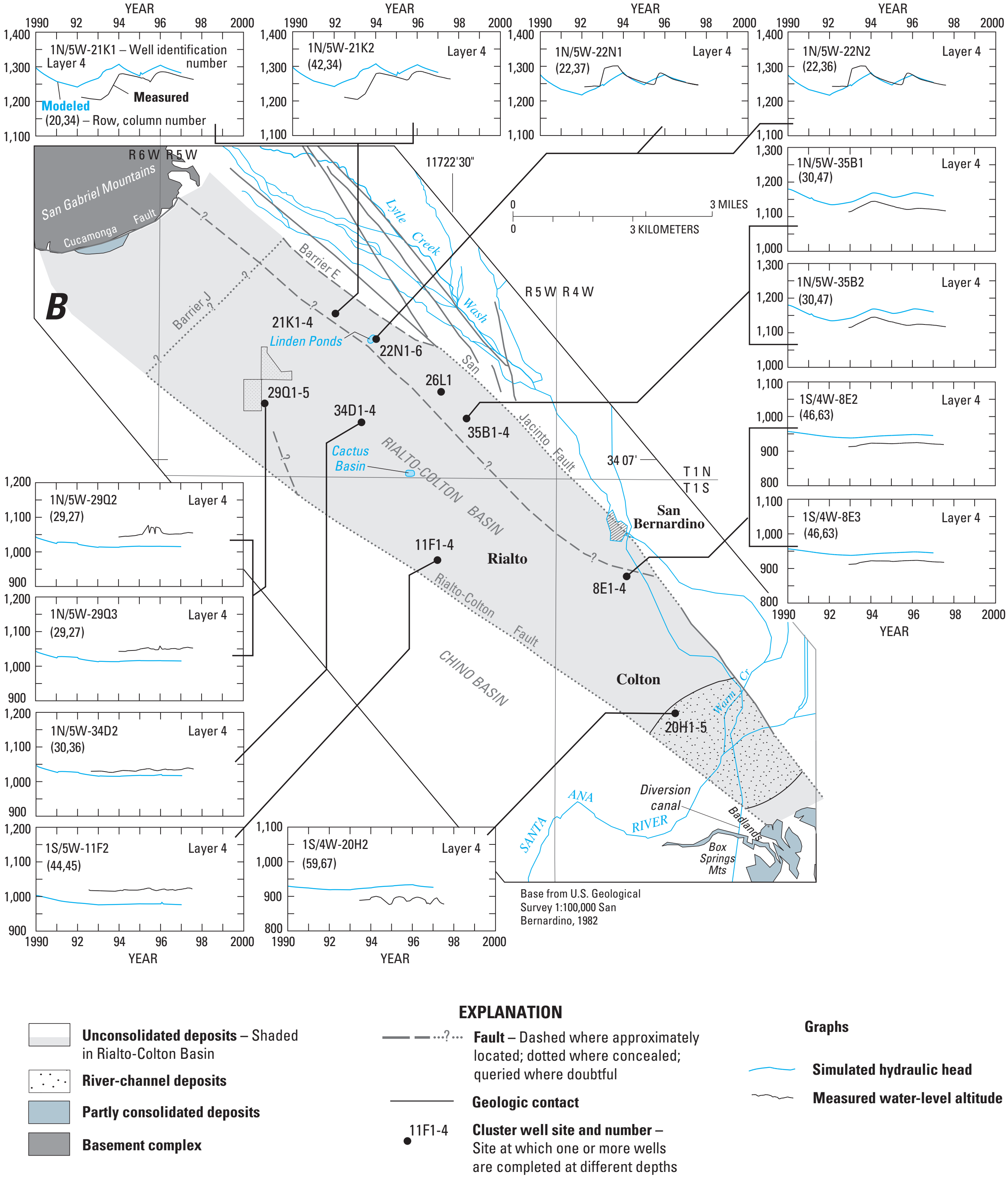


Figure 27. Location of wells, and hydrographs showing simulated heads and measured water-level altitudes (in feet above sea level) for selected cluster wells in layers 1–3 ***(A)***, and layer 4 ***(B)***, in the Rialto–Colton Basin, San Bernardino County, California.



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underflow from the Lytle Basin are simulated as wells with positive flow rates; these effects occur instantaneously in the model. Therefore, the lag time (about 6 months) between the onset of the recharge event and the water-level response (fig. 11) is not accounted for in the model. Also, the water-level response to individual artificial-recharge events may not be simulated adequately with annual stress periods. In addition, the simulated water-level peaks after the 1992 recharge event occurred later than the measured water-level peaks in most wells in the compartment between the San Jacinto Fault and the unnamed fault, indicating that the spatial and temporal distribution of recharge is not well understood. Simulated heads were about 10 to 50 ft too low in the rest of the basin (wells 1N/5W-34D3-4, 1N/5W-29Q3-4, and 1S/4W-11F3-4), implying insufficient recharge to layer 3 in the northwestern part of the basin west of the unnamed fault. Near Warm Creek, water levels were about 20 ft too high (well 1S/4W-20H3) (fig. 27), implying too much recharge to layer 3 in this area.

Differences between simulated head and measured water level in layer 4 in the compartment between the unnamed fault and the San Jacinto Fault varied with location (fig. 27). At the artificial-recharge ponds, simulated heads were lower than measured heads at wells 1N/5W-22N1,2 during 1992–94 but compared well during 1994–96. Upgradient from the recharge ponds, water-level differences generally were within 20 ft except during 1992–94 at wells 1N/5W-21K1,2. Simulated heads downgradient from the recharge ponds were 25 to 50 ft higher than measured water levels (wells 1N/5W-35B1,2 and 1S/4W-8E2). Simulated heads were about 15 to 50 ft lower than measured water levels in layer 4 in the rest of the basin (wells 1N/5W-29Q2,3, 1N/5W-34D2, and 1S/5W-11F2) (fig. 27).

Differences between simulated heads and measured water levels may be attributed to several factors. These differences indicate that (1) the distribution of recharge in layer 3 may not be adequately simulated; (2) there may be a source of recharge to layer 3 and (or) layer 4 that is not simulated; (3) there may exist aquifer heterogeneities that are not simulated in the model; (4) the hydraulic-conductivity values should be higher in the recharge areas; and (or) (5) the storage-coefficient values should be higher in the recharge areas. The only source of recharge to layer 4 that is simulated in the model is vertical movement of water from layer 3; hence, water levels in layer 4 are affected by recharge patterns in layer 3. Values of hydraulic conductivity and storage coefficient were not increased beyond those shown in figures 20 and 23, respectively, during model calibration because available data do not support the higher values.

The simulated potentiometric contours in the Rialto–Colton Basin are shown in figure 28 for initial conditions (1945). Contour lines for layer 1 (fig. 28*A*) show that ground water moves westward in this layer from the Bunker Hill Basin to the North Riverside Basin.

The simulated potentiometric contours for layer 2 are shown in figure 28*B*. Ground water moves southwestward and southeastward across the unnamed fault and upward from layer 3 at the northeastern boundary of layer 2. Near the Santa Ana River and Warm Creek, ground water moves westward from the Bunker Hill Basin to the North Riverside Basin.

The simulated potentiometric contours for layer 3 are shown in figure 28*C*. Ground water moves across Barrier E from the Lytle Basin in the northwestern part of the basin and then moves southward and southwestward north of Barrier J. South of Barrier J, ground water moves in a southeastward direction along the axis of the basin. In the southeastern part of the basin, ground water moves in a westward direction across the Rialto–Colton Fault to the North Riverside Basin. Water levels east of the unnamed fault were 25 to 100 ft higher than those west of the fault.

The simulated potentiometric contours for layer 4 are shown in figure 28*D*. Ground water southeast of Barrier J moves from northwest to southeast along the axis of the basin. Water levels east of the unnamed fault were about 50 to 100 ft higher than those west of the fault. The source of recharge to layer 4 in the model is downward movement of water from layer 3. Discharge from layer 4 is from pumpage or upward movement of ground water to layer 3 in the southeastern part of the basin.

Simulated 1996 potentiometric contours for layers 1 and 2 are shown in figure 29. In layer 1, ground water moves westward from the Bunker Hill Basin to the North Riverside Basin (fig. 29*A*). In layer 2, ground water moves southeastward from the unsaturated part of layer 2 (fig. 29*B*). In the vicinity of the Santa Ana River and Warm Creek, ground water moves westward

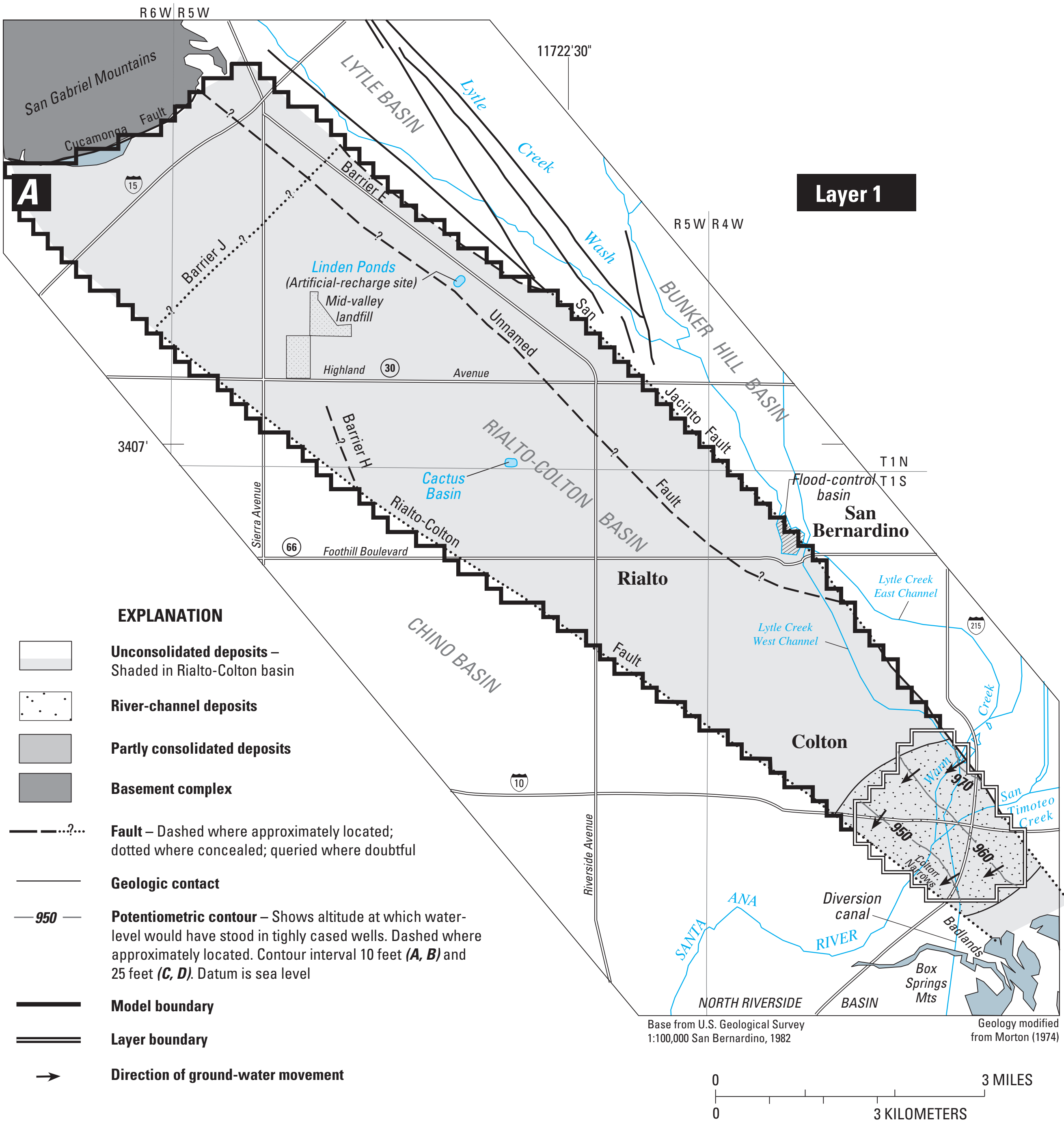
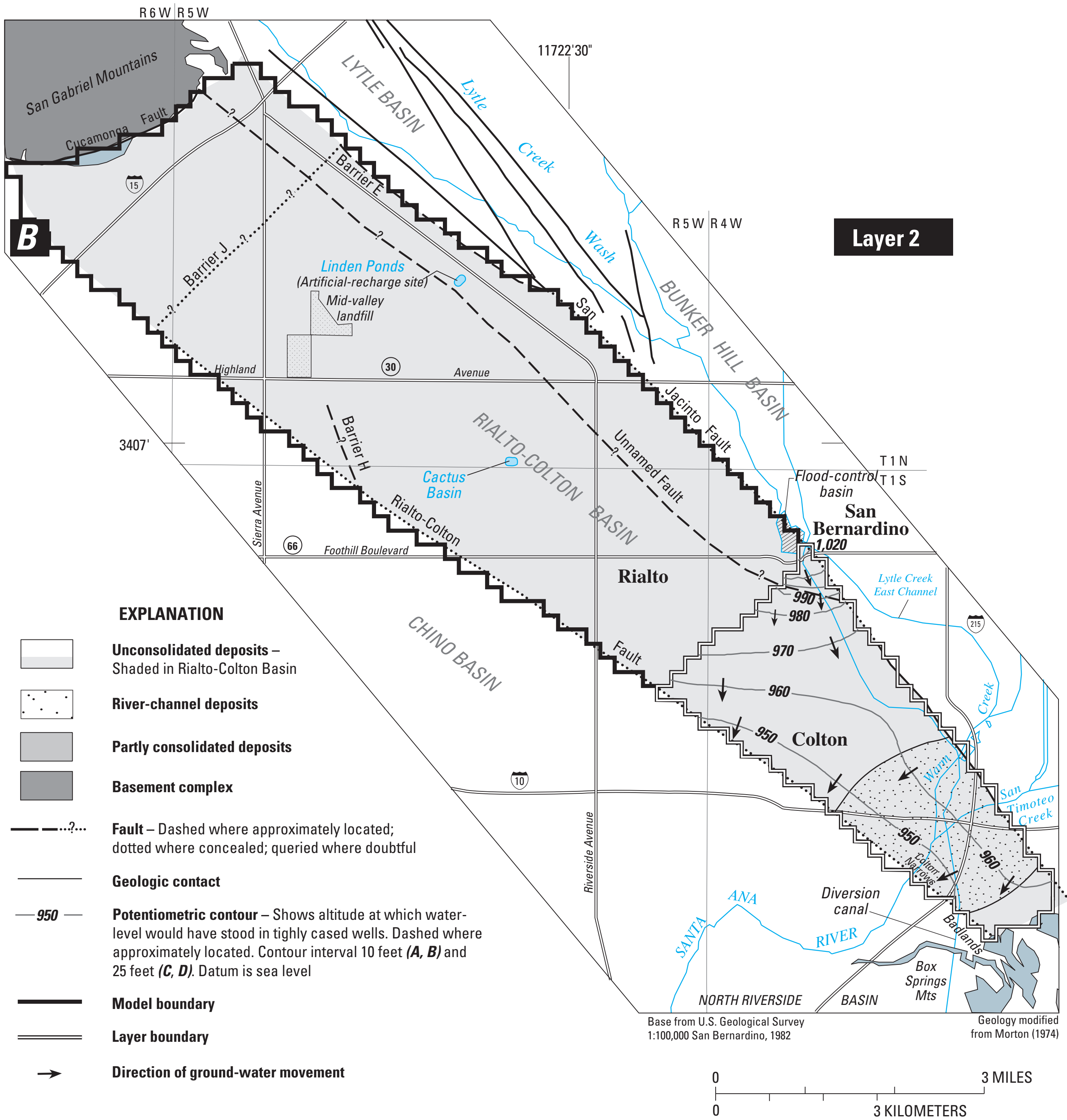


Figure 28. Simulated potentiometric contours for layers 1–4 (***A–D***), 1945, in the Rialto–Colton Basin, San Bernardino County, California.



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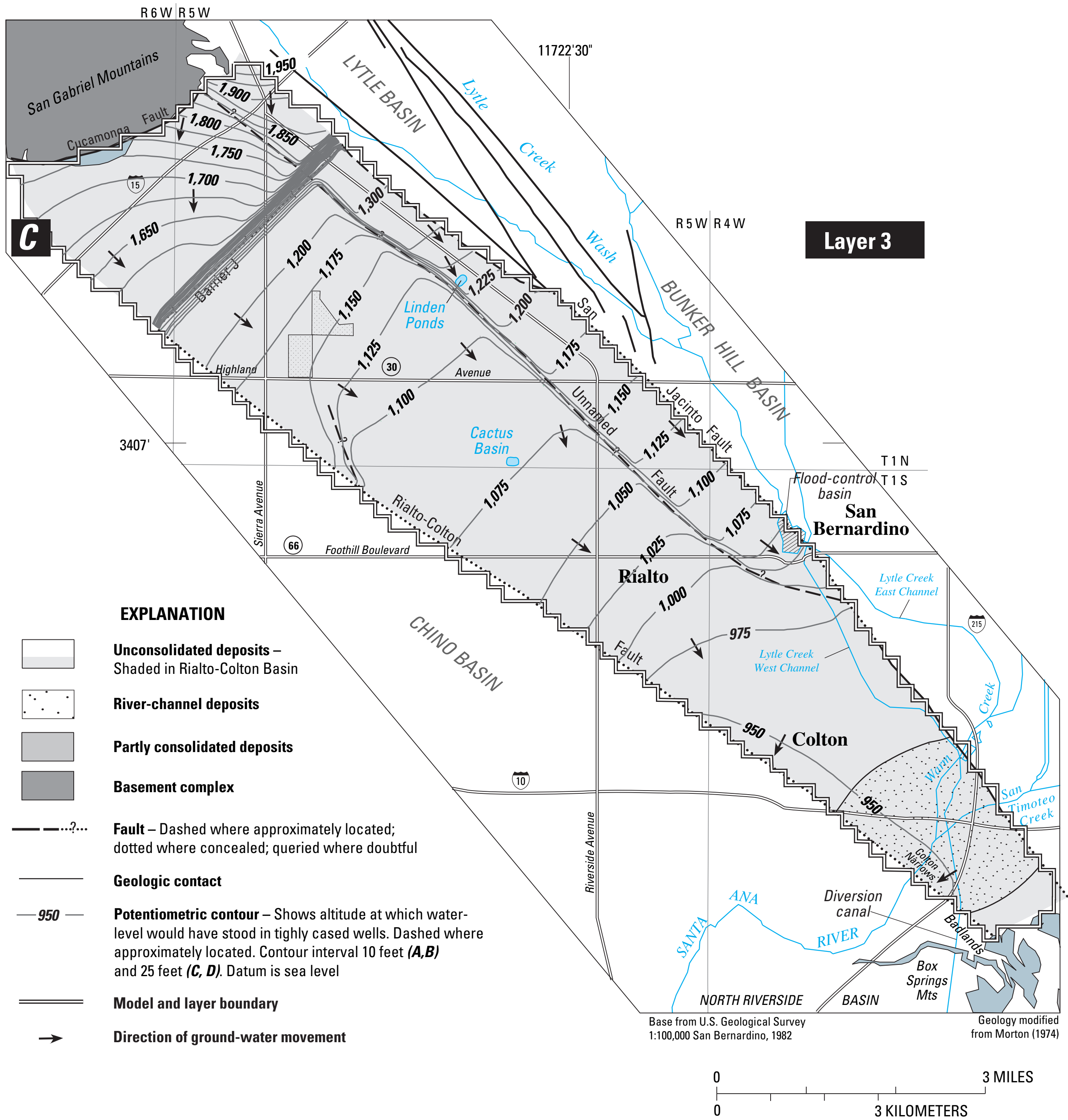

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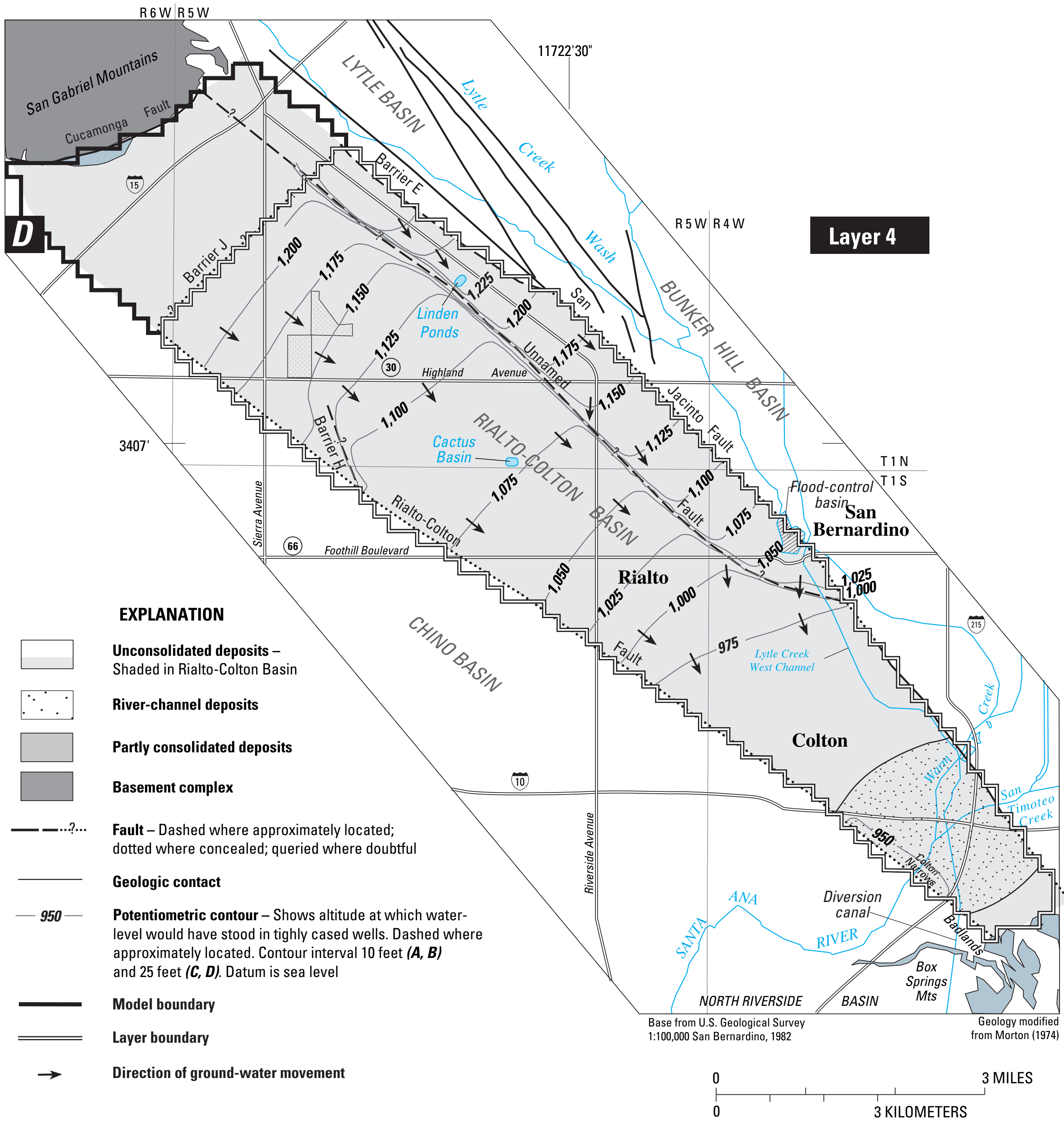

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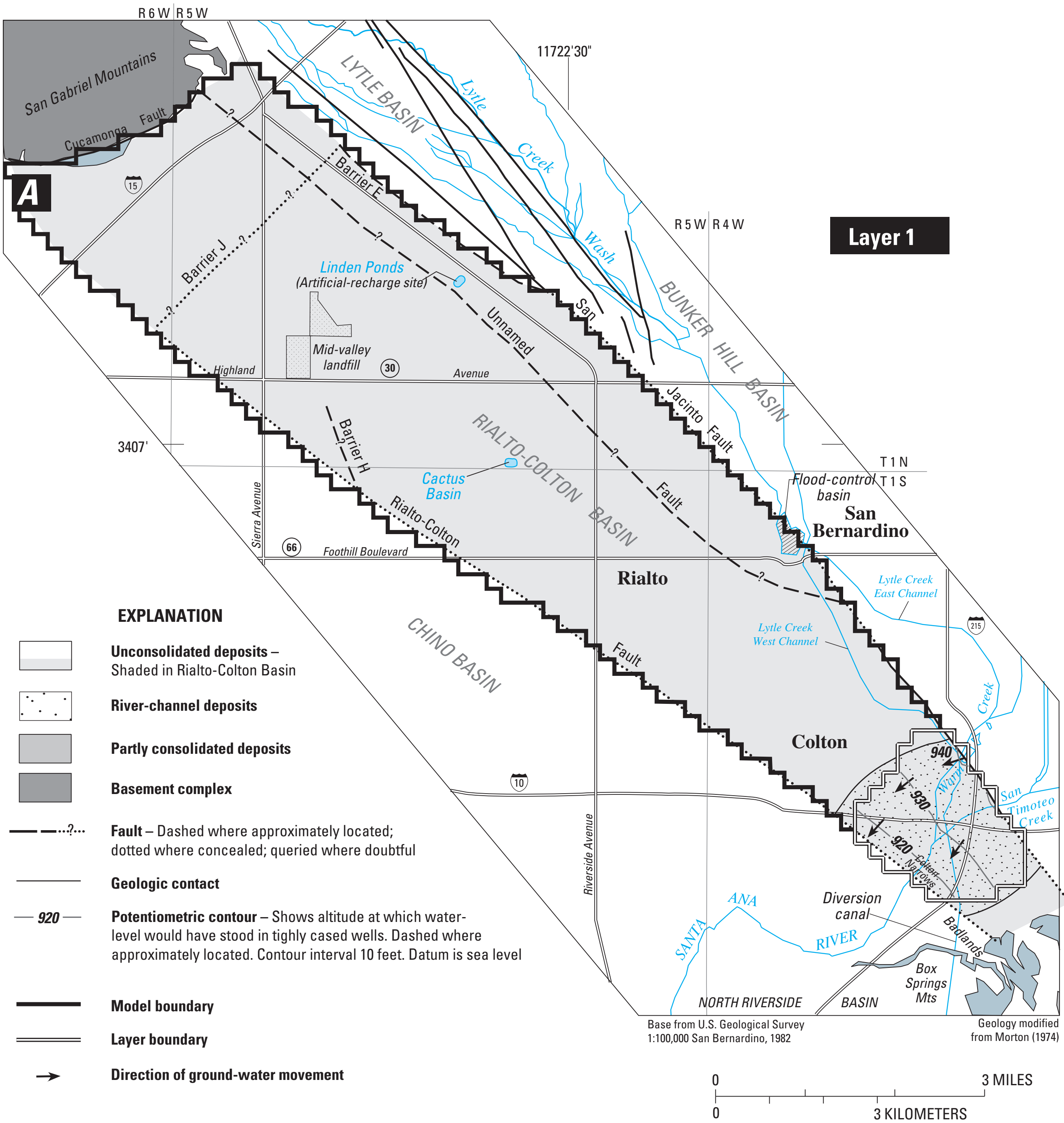

Figure 29. Simulated potentiometric contours for layers 1 and 2 (***A,B***), 1996, in the Rialto–Colton Basin, San Bernardino County, California.

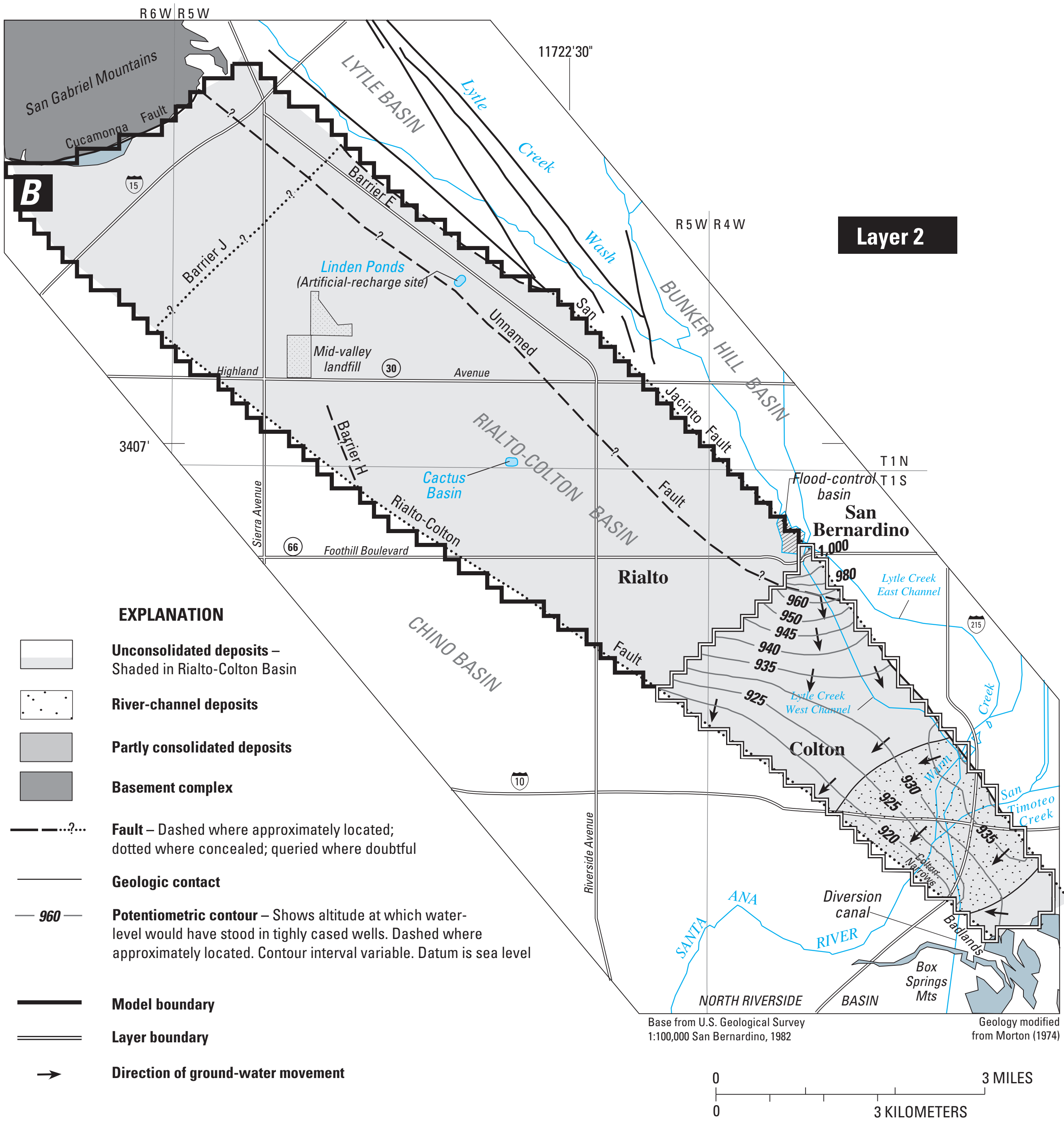

Figure 29.—Continued.

from the Bunker Hill Basin to the North Riverside Basin. Ground-water levels in layers 1 and 2 in 1945 were about 5 to 15 ft lower than those in 1996.

Simulated 1996 potentiometric contours for layers 3 and 4 are shown in figure 30. In layer 3, ground water moves generally southward northwest of Barrier J (fig. 30*A*). Ground water moves southeastward southeast of Barrier J. Water levels east of the unnamed fault were from 50 to 200 ft higher than those west of the fault. Water levels in 1945 ranged from about 25 to 50 ft higher than those in 1996, except east of the unnamed fault where water levels were as much as 25 ft higher in 1996 (fig. 30*A*). In layer 4, ground water moves southeastward southeast of Barrier J (fig. 30*B*). Water levels east of the unnamed fault were about 50 to 200 ft higher than those southwest of the fault. Water levels in 1945 ranged from about 25 to 50 ft higher than those in 1996 except east of the unnamed fault (fig. 30*B*).

Simulated Water Budgets

A summary water budget of all simulated recharge and discharge components input into or calculated by the flow model for initial conditions (1945), average 1945–96 transient-state conditions, and 1996 transient-state conditions is presented in table 11. Recall that for all simulations, ungaged runoff and subsurface inflow, irrigation return flow, areal recharge, artificial recharge, pumpage, and evapotranspiration are input to the model. Recall also that irrigation return flow is accounted for in the model by calculating net pumpage, which is the total pumpage minus the water that is returned to the system. As mentioned in the "Irrigation Return Flow" section of this report, the return-flow factor is 30 percent; therefore, the net-pumpage values are 70 percent of total-pumpage values. Underflow from the Lytle Basin to the Rialto–Colton Basin and from the Bunker Hill Basin to the Rialto–Colton Basin was determined from model calibration. The model simulates outflows from the general-head boundary, stream recharge and discharge, and flow to and from storage.

Total recharge to the basin was about 34,920 acre-ft in 1945 under initial conditions. Underflow from the Bunker Hill Basin accounted for about 39 percent of the total recharge; and underflow from the Lytle Basin accounted for about 31 percent (fig. 31). Seepage loss from the Santa Ana River and Warm Creek and mountain-front recharge each contributed 9 percent of total recharge in 1945 (fig. 31). Average total recharge during 1945–96 was about 33,620 acre-ft. Underflow from the Lytle and Bunker Hill Basins accounted for a lesser percentage of total recharge during 1945–96 (60 percent) than during 1945 (70 percent) (fig. 31). The quantity of underflow from both the Bunker Hill and Lytle Basins (20,300 acre-ft) was about 18 percent less than the 1945 quantity (24,620 acre-ft). The quantities of underflow from the Bunker Hill and Lytle Basins during 1945–96 were about 17 and 19 percent less, respectively, than in 1945. During 1945–96, average total pumpage (11,080 acre-ft) also was greater than in 1945 (6,791 acre-ft); this increased pumpage may have created steeper hydraulic gradients in layers 1 and 2 in the vicinity of the Santa Ana River and Warm Creek, inducing greater quantities of water to move from the Bunker Hill Basin to the Rialto–Colton Basin. Total recharge during 1996 was about 31,830 acre-ft. The quantity of underflow from both the Lytle Basin (8,560 acre-ft) and the Bunker Hill Basin (9,550 acre-ft) in 1996 was less than the long-term average, owing, in part, to less-than-average discharge in Lytle Creek, which contributes to underflow from the Lytle Basin, and a relatively shallow hydraulic gradient across the southeastern part of the basin. The discharge in Lytle Creek in 1996 was 24,400 acre-ft, which is 7,940 acre-ft less than the 1945–96 average (USGS ADAPS database). The hydraulic gradient between wells 1S/4W-3Q1 and 1S/4W-29H2 was 0.005 during 1996, which was less than the 1945–96 average (0.006).

Model-calculated seepage loss from the Santa Ana River and Warm Creek was 3,260 acre-ft, about 9 percent of total recharge for initial conditions in 1945 (fig. 31). The average seepage loss for 1945–96 was 4,860 acre-ft, about 15 percent of the average total recharge (fig. 31). The quantity of seepage loss in 1996 was 5,490 acre-ft, accounting for 18 percent of total recharge to the Rialto–Colton Basin (fig. 31). The quantity of seepage loss from the Santa Ana River and Warm Creek varied significantly during 1945, 1945–96, and 1996, indicating that relatively high ground-water levels caused more water to remain in the stream channel and leave the Rialto–Colton Basin as surface flow during 1945 than during the 1945–96 average period and 1996.

Total discharge for 1945 initial conditions was about 34,940 acre-ft. Underflow from the Rialto–Colton Basin to the Chino and North Riverside Basins

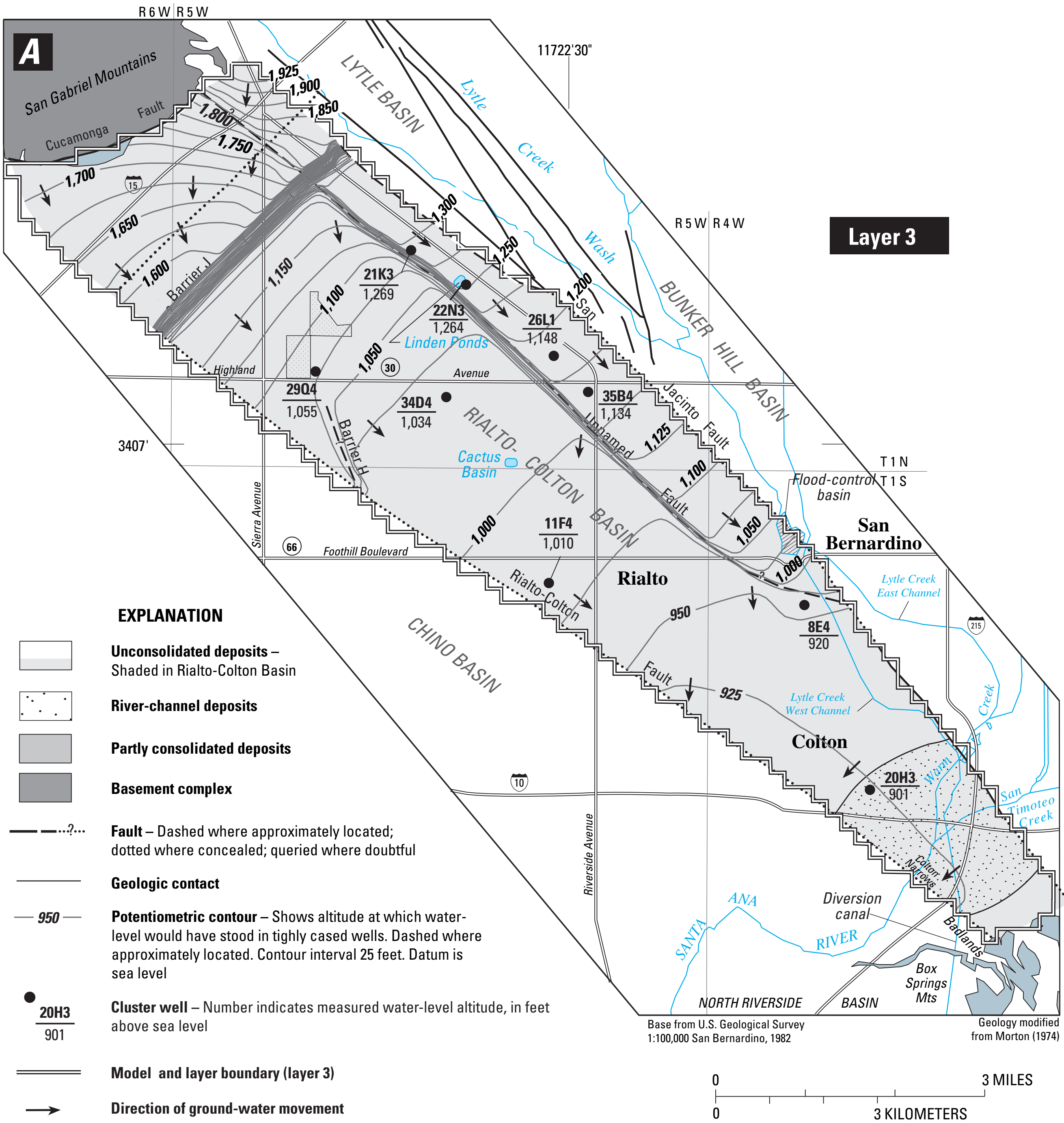

Figure 30. Measured water-level altitudes and simulated potentiometric contours for layers 3 and 4 (***A,B***), 1996, in the Rialto–Colton Basin, San Bernardino County, California.

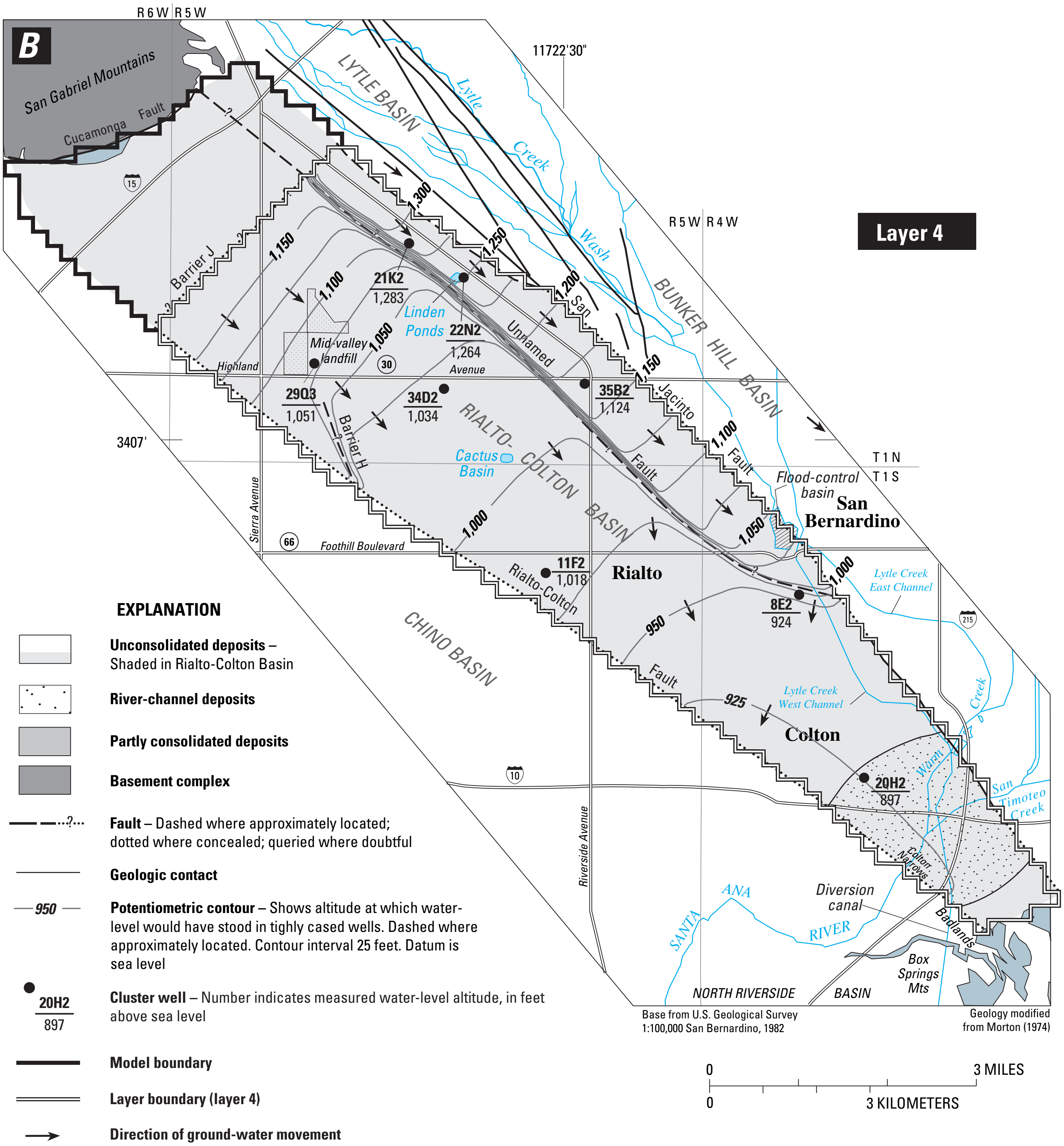

Figure 30.—Continued.

Table 11. Model-simulated initial conditions and transient water budgets for the Rialto–Colton Basin, San Bernardino County, California

[Budget values in acre-feet; —, no value; <<, much less than]

	Initial conditions	Transient	
	1945	1945–96 average	1996
Recharge			
Underflow from Lytle Basin			
North of Barrier J	5,480	4,460	4,280
South of Barrier J	5,480	4,460	4,280
Total	10,960	8,920	8,560
Underflow from Bunker Hill Basin			
Layer 1	10,930	9,100	7,640
Layer 2	2,730	2,280	1,910
Total	13,660	11,380	9,550
Seepage loss from the Santa Ana River and Warm Creek	3,260	4,860	5,490
Ungaged runoff and subsurface inflow			
San Gabriel Mountains	2,930	2,950	2,550
Badlands	90	120	90
Total	3,020	3,070	2,640
Irrigation return flow	2,040	3,320	4,730
Imported water	—	750	0
Seepage loss from diversion canal	1,120	190	—
Areal recharge	860	860	860
Underflow from Chino Basin			
Layer 1	0	20	0
Layer 2	0	130	0
Layer 3	0	120	0
Total	0	270	0
Total recharge	34,920	33,620	31,830
Water from storage	—	7,350	11,110
Discharge			
Total pumpage	6,790	11,080	15,760
Underflow to Chino and North Riverside Basins			
Layer 1	4,100	4,670	4,880
Layer 2	10,280	9,460	10,760
Layer 3	10,300	9,570	10,800
Total	24,710	23,700	26,440
Seepage loss to the Santa Ana River and Warm Creek	3,440	440	0
Evapotranspiration	<<1	<<1	<<1
Total discharge	34,940	35,220	42,200
Water to storage	—	5,960	720
Recharge - Discharge	–20	[2]–1,600	–[2]10,370
Storage depletion	0	1,390	10,390

[1] The difference between recharge and discharge in this simulation should be 0. The observed differences are due to accumulation of small consistent errors in the model and rounding of numbers.

[2] The difference between recharge and discharge should be equal to the storage depletion. The observed differences are due to accumulation of small consistent errors in the model and rounding of numbers.

was the main component of discharge for 1945 initial conditions, accounting for 71 percent of the total discharge (fig. 32). Total pumpage accounted for 19 percent of total discharge, and seepage loss to the Santa Ana River and Warm Creek for 10 percent (fig. 32). Average total discharge for 1945–96 was about 35,220 acre-ft. Underflow accounted for about 68 percent of total discharge, and total pumpage accounted for about 31 percent (fig. 32). Seepage loss to the Santa Ana River and Warm Creek only accounted for 1 percent of discharge. Total pumpage in the Rialto–Colton Basin varied about the average during 1949–71, and then increased during 1984–96 (fig. 13), owing, in part, to the drought in California during 1987–92. Pumpage in 1996 (15,760 acre-ft) accounted for 37 percent of total discharge, and underflow to the Chino and North Riverside Basins (26,440) accounted for 63 percent (fig. 32). The increase in pumpage and decrease in underflow in 1996 probably is due to less-than-average rainfall.

During 1945–96, the average annual quantity of water removed from storage exceeded the average annual quantity that went into storage, resulting in an average storage depletion in the basin of 1,390 acre-ft. During 1996, about 11,110 acre-ft of recharge was removed from storage and about 720 acre-ft went into

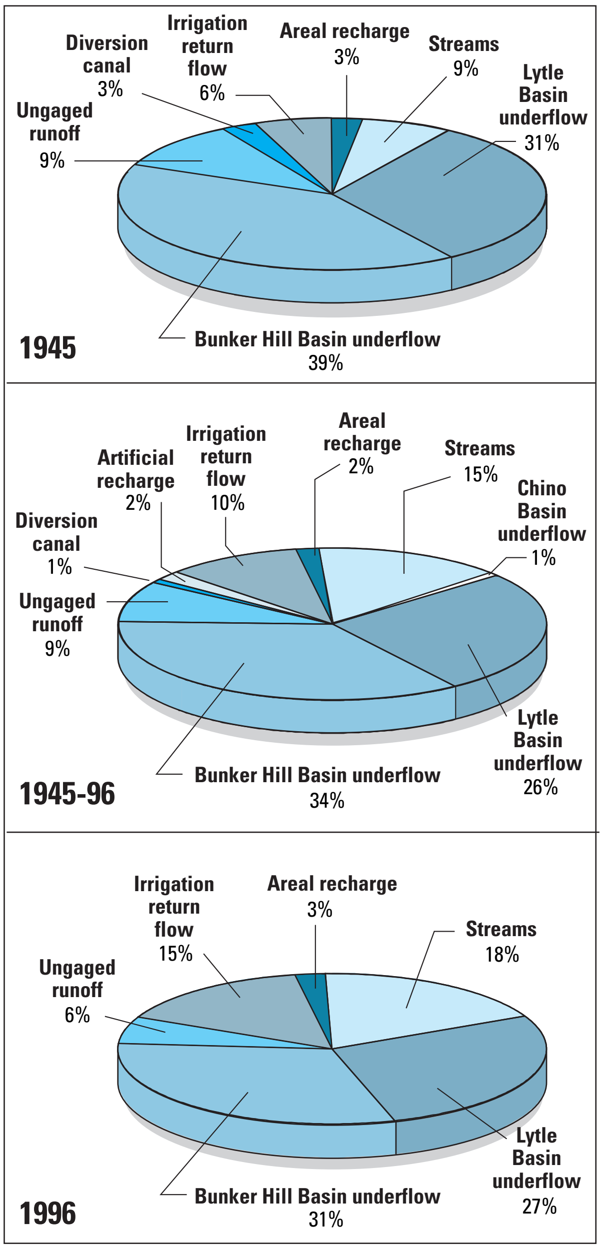

Figure 31. Components of recharge in the Rialto–Colton Basin, San Bernardino County, California.

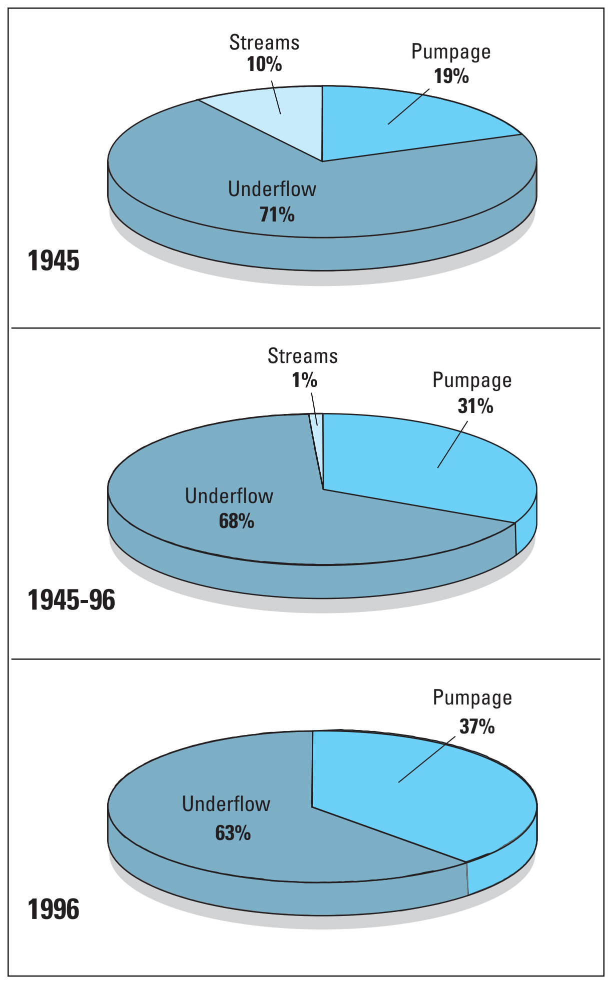

Figure 32. Components of discharge in the Rialto–Colton Basin, San Bernardino County, California.

storage. During the 1987–92 drought, basin storage probably was depleted in some areas owing to decreased recharge and increased pumping during this period, allowing recharge during the subsequent years to refill in these areas of the basin, thus accounting for the quantity of water going into storage. Total discharge exceeded total recharge by about 10,370 acre-ft during 1996 owing to increased pumpage and decreased recharge from underflow from the Lytle and Bunker Hill Basins.

Sensitivity Analysis

The sensitivity of the Rialto–Colton model was determined for changes in total recharge (defined as the sum of underflow from the Lytle and Bunker Hill Basins, ungaged runoff, and areal recharge), net pumpage, irrigation return flow, hydraulic conductivity, vertical conductance, primary and secondary storage coefficients, general-head boundary conductance, horizontal-flow-barrier characteristic, artificial recharge, and streambed conductance. These model parameters (subsequently referred to as "inputs") were varied individually while holding the remaining inputs

Table 12. Sensitivity of hydraulic head in the Rialto–Colton Basin model (1996), San Bernardino County, California, to changes in model input

[Range of changes in feet, and range numbers are separated by slash (/); unsigned numbers in range of change are positive or zero and indicate increases or no change (zero) from values in the calibrated model, negative numbers indicate declines; rank (in parentheses) from most sensitive (1) to least (21); —, barrier either on or off]

Model input	Factor of change model	Range of change in hydraulic head and calibrated head, and rank			
		Layer 1	Layer 2	Layer 3	Layer 4
[1]Total recharge	2.0	44/15 (1)	73/14 (1)	453/14 (1)	211/19 (3)
[1]Total recharge	.75	–3/–7 (8)	–3/–19 (7)	–3/–74 (6)	–4/–61 (6)
Irrigation return flow	2.0	4/2 (9)	10/2 (11)	42/1 (9)	39/2 (10)
Irrigation return flow	.5	–1/–2 (12)	–1/–5 (15)	–.5/–21 (14)	–1/–24 (13)
Hydraulic conductivity	1.25	.6/–4 (7)	.6/–12 (9)	14/–52 (10)	.4/–53 (7)
Hydraulic conductivity	.75	6/–9 (4)	17/–1 (6)	76/–10 (4)	78/–.3 (4)
Vertical conductance	.5	.9/–.2 (11)	4/–.6 (14)	8/–1 (19)	20/–10 (11)
Vertical conductance	2.0	.1/–.6 (13)	.4/–3 (17)	.6/–6 (21)	8/–14 (14)
Primary storage coefficient	2.0	.3/.1 (19)	.8/.1 (20)	12/–3 (16)	3/.1 (20)
Primary storage coefficient	.5	0/–.1 (20)	0/–.8 (19)	0/–8 (20)	0/–1 (21)
Secondary storage coefficient	2.0	.3/–.1 (18)	1/–3 (16)	4/–14 (15)	4/–13 (16)
Secondary storage coefficient	.5	–.2/–.8 (15)	–.1/–1 (18)	9/–3 (17)	1/–3 (19)
General-head boundary conductance	.1	46/30 (3)	66/31 (4)	–.6/65 (7)	61/24 (9)
General-head boundary conductance	10	–6/–13 (5)	–6/–13 (13)	7/–20 (12)	–3/–19 (17)
All faults are not barriers	—	–.4/–1 (16)	4/–47 (2)	0.6/–373 (2)	54/–167 (1)
No unnamed fault	—	–.2/–0.7 (17)	6/–45 (3)	71/–320 (3)	61/–160 (2)
No Barrier H	—	0/0 (21)	0/0 (21)	9/–61 (5)	7/–59 (5)
Artificial recharge	2.0	2/0.6 (10)	15/0.6 (8)	50/–0.1 (8)	49/0.8 (8)
Artificial recharge	.5	–.3/–1 (14)	–0.3/–8 (12)	0.1/–26 (13)	–0.4/–26 (12)
Streambed conductance	.1	–4/–10 (6)	–1/–10 (10)	0/–10 (18)	–0.8/–9 (18)
Streambed conductance	10	32/11 (2)	31/3 (5)	28/–0.1 (11)	22/2 (15)

[1]Total recharge is the sum of underflow from Lytle and Bunker Hill Basins, ungaged runoff, and areal recharge.

at their calibrated values. In general, the amount of variation for a particular input was based on reasonable ranges of values that would be expected in the natural system. Vertical conductance was varied at 0.5 and 2.0 times its calibrated values. General-head boundary conductance and streambed conductance were varied at 0.1 and 10 times their calibrated values. Total recharge and hydraulic conductivity were varied at 0.75 and 2.0 times their calibrated values. Artificial recharge was varied at 0.5 and 2.0 times its measured value. Primary and secondary storage coefficients were varied at 0.5 and 2.0 times their calibrated values. Greater variation in the total recharge, in vertical conductance, in the hydraulic conductivity, and in the primary and secondary storage coefficients, caused instability in the model, and the solution failed to converge. Aquifer parameters were not varied for individual layers; the values were either increased or decreased in all layers for a given sensitivity run. Horizontal-flow-barrier hydraulic characteristics for all faults, the unnamed fault and Barrier H each were set to a value of 1×10^{30} to represent no-barrier conditions. The sensitivity of the model to changes in irrigation-return flow and net pumpage was determined by variation of the irrigation return flow. An increase in the irrigation-return-flow factor is equivalent to a decrease in net pumpage. The converse also is true. The irrigation-return-flow factor was varied at 2.0 and 0.5 times its calibrated value (30 percent).

A sensitivity analysis was performed on an ongoing basis during the calibration process in order to determine the model areas, as well as inputs, that were most important in affecting model-generated hydraulic heads at the calibration wells. In addition, considerable calibration effort was placed on determining reasonable values for those items that were both the most sensitive and the least well known: underflow from the Lytle and Bunker Hill Basins, underflow to the Chino and North Riverside Basins, and hydraulic characteristics of faults. Results presented in table 12 are those from the final sensitivity analysis of the calibrated transient (1945–96) model. The maximum and minimum head given in table 12 are the maximum and minimum differences between the calibrated head and the head simulated from changes in model inputs.

The sensitivities of hydraulic head to changes in inputs are presented in table 12. Sensitivity is ranked from 1 to 21, whereby the lowest rank indicates the most sensitive (largest deviation from zero) input and the highest rank indicates the least sensitive (smallest deviation from zero) input. The hydraulic heads in layers 1 and 2 are most sensitive to an increase (2.0×) the total recharge (rank 1). The hydraulic heads in layer 1 also are sensitive to an increase (10×) in the streambed conductance (rank 2), a decrease (0.1×) in the general-head boundary conductance (rank 3), and a decrease (0.75×) in the hydraulic conductivity (rank 4). Hydraulic heads in layer 2 also are sensitive to the removal of all internal faults (no barrier effect) (rank 2), the removal of the unnamed fault (no barrier effect) (rank 3), and a decrease (0.1×) in the general-head boundary conductance (rank 4). Hydraulic heads in layer 1 are least sensitive to a decrease (0.5×) in the primary storage coefficient (rank 20) and the removal of Barrier H (rank 21). Hydraulic heads in layer 2 are least sensitive to an increase (2.0×) in the primary storage coefficient (rank 20) and the removal of Barrier H (rank 21).

Hydraulic heads in layer 3 are most sensitive to an increase (2.0×) in total recharge (rank 1) and removal of all internal faults (no barrier effect) (rank 2). Hydraulic heads in layer 3 also are sensitive to removal of the unnamed fault (rank 3), and a decrease (0.75×) in the hydraulic conductivity (rank 4). Hydraulic heads in layer 4 are most sensitive to the removal of all internal faults (rank 1) and the removal of the unnamed fault (rank 2). Hydraulic heads in layer 4 also are sensitive to an increase (2.0×) in total recharge (rank 3), and a decrease (0.75×) in hydraulic conductivity (rank 4). Hydraulic heads in layer 3 are least sensitive to a decrease (0.5×) in the primary storage coefficient (rank 20) and an increase (2.0×) in the vertical conductance (rank 21). Hydraulic heads in layer 4 are least sensitive to an increase (2.0×) in the primary storage coefficient (rank 20) and a decrease (0.5×) in the primary storage coefficient (rank 21).

The relative sensitivity of hydraulic heads in layer 3 to an increase (rank 2) or decrease (rank 6) in total recharge may, at least in part, explain why the model-generated heads just southeast of Barrier J generally are too high during 1955–82 (for example, 1N/5W-27D1 and 1N/5W-34B1) and, in the central part of the basin, generally are too low during 1982–96 (for example, 1S/5W-2K1 and 1S/5W-5A2). The largest increase or decrease in heads occurred in the recharge area northwest of Barrier J. In addition, hydraulic heads near the Santa Ana River and Warm Creek are too high during most of the simulation period (except during 1965–72). The relative sensitivity in hydraulic heads to the variation in total recharge (rank 1 for layers 1,2,and 3, and rank 4 for layer 4 to an increase in total recharge, and rank 6 for layers 3 and 4, and rank 7 and 8, respectively, for layers 2 and 1 to a decrease in total recharge) may explain, in part, this temporal distribution of model-generated heads, thus indicating that the spatial and temporal distribution of recharge may not be completely accurate.

SIMULATED EFFECTS OF ARTIFICIAL-RECHARGE ALTERNATIVES ON GROUND-WATER LEVELS AND MOVEMENT

Predictive simulations for the Rialto–Colton Basin were run for three artificial-recharge alternatives: continued artificial recharge at Linden Ponds, discontinued artificial recharge, and artificial recharge at Cactus Basin. To extend the ground-water flow model beyond 1996, average hydrologic conditions (natural recharge and discharge) for 1945–96 were used for the predictive simulation period, 1997–2027. Because artificial-recharge operations were discontinued at Linden Ponds in 1995, artificial-recharge values for 1995–99 are zero. The predictive ground-water flow model for the Rialto–Colton Basin (1997–2027) was used to simulate the water-level response in selected wells to continued artificial recharge at Linden Ponds and artificial recharge at Cactus Basin. Projected artificial recharge begins in 1997, and the temporal pattern of artificial recharge used was repetition of the artificial-recharge quantities from 1982–96 recharge pattern twice during 2000–2027 (see 1982–96 recharge pattern—"recharge pattern 1", table 13), with zero recharge quantities from 1997 through 1999. The discontinued recharge pattern ("recharge pattern 2") consists of zero recharge for each year during 2000–27 (table 13). As described in the "Recharge" section of this report, artificial recharge in Linden Ponds is simulated using the well package, and the recharge quantities are assigned equally to two cells, (21, 37) and (22, 37), in layer 3. Artificial recharge in Cactus Basin also is simulated using the same recharge rate and pattern as was used at Linden Ponds. The well package was used to simulate artificial recharge, and the recharge quantities are assigned equally to cells (34, 42) and (35, 42) in layer 3. Water-level responses in layer 3 (the main producing unit) are evaluated at selected cluster and production wells. For comparison, simulated heads using discontinued artificial recharge are shown on all hydrographs.

Results from the predictive simulations were used in conjunction with the computer model MODPATH (Pollock, 1994) to simulate advective transport of nonreactive constituents in imported water within the

Table 13. Actual and projected quantities of artificial recharge in Linden Ponds and Cactus Basin, San Bernardino County, California, 1997–2027

[Recharge quantities are in acre-feet]

Year	Recharge pattern 1	Recharge pattern 2
1997	0	0
1998	0	0
1999	0	0
2000	3,220	0
2001	4,736	0
2002	3,471	0
2003	3,879	0
2004	5,345	0
2005	3,030	0
2006	4,601	0
2007	4,522	0
2008	65	0
2009	435	0
2010	1,559	0
2011	3,747	0
2012	261	0
2013	0	0
2014	0	0
2015	0	0
2016	3,220	0
2017	4,736	0
2018	3,471	0
2019	3,879	0
2020	5,345	0
2021	3,030	0
2022	4,601	0
2023	4,522	0
2024	65	0
2025	435	0
2026	1,559	0
2027	3,747	0

Rialto–Colton Basin. MODPATH, which computes pathlines and travel distances, was used to track the movement of the imported water in layer 3 using a particle-tracking technique and the results of the ground-water flow model simulations. Layer 3 was selected because the imported water is recharged to layer 3; it also represents the main water-producing unit in the basin. To assess the effect that artificial recharge of imported water has on ground-water flow directions and the distance traveled, particle tracking was simulated using the same two temporal artificial-recharge patterns mentioned previously at Linden Ponds and recharge pattern 1 at Cactus Basin. In addition, particle tracking was simulated assuming discontinued artificial recharge in the Rialto–Colton Basin (recharge pattern 2). Because average values for stresses were used for the predictive simulation, a net-pumpage value was assigned to all wells. Therefore, a well that was inactivated or destroyed sometime during 1945–96 may capture some of the imported water.

The use of MODPATH in this analysis assumes, as is generally valid for high-permeability systems such as layer 3 in the Rialto–Colton Basin, that the influence of advection will be much more important than that of dispersion. The use of MODPATH also assumes that hydraulic heads and the magnitude and direction of the flow velocity at any point in the model are constant throughout the simulation; in reality, however, hydraulic heads and flow velocities are known to be increasing or decreasing in response to ground-water pumping and (or) artificial recharge. It also was assumed that the lithology within a cell is constant, and that particles are stopped when they enter cells where discharge to sinks is larger than 25 percent of the total flow to the cell. It must be emphasized that particle-tracking simulations provide only a general indication of relative rates and directions of solute movement.

Aquifer porosity is a required input for MODPATH simulations. Because estimates of porosity in the unconsolidated deposits of layers 1, 2, and 4 are not available for the Rialto–Colton Basin, porosities used in MODPATH were based on ranges of values for materials published by Freeze and Cherry (1979, p. 37). A porosity of 40 percent was used for model layer 1 and is within the range of values for gravel (25 to 40 percent) and sand (25 to 50 percent) with interbedded clay (40 to 70 percent), which are found in the river-channel deposits. The porosity assigned to layer 2 is 35 percent, which is within the range for gravel and sand. A porosity of 45 percent, which probably is representative of the fine-grained material found in the lower water-bearing unit, was used for layer 4.

For layer 3, porosity was estimated using model-calibration techniques. Historical stable-isotope and tritium data for 1993 indicate that the imported water had moved as far as well 1N/5W-26L1 (about 1.5 mi from Linden Ponds) since 1982 along the axis of the basin between the unnamed fault and the San Jacinto Fault (Woolfenden, 1994). Movement probably occurs preferentially in the coarse-grained deposits within the middle water-bearing unit. In the particle-tracking model, a porosity of 30 percent or less was needed to duplicate the 1993 conditions; a porosity of 30 percent resulted in a simulation of imported-water movement no farther than well 1N/5W-26L1. Smaller values of porosity resulted in greater distances of imported-water movement. To provide a conservative estimate of the distance traveled by the imported water, a porosity of 30 percent was chosen for simulation of the artificial-recharge alternatives. A porosity value of 30 percent also is within the range for the sand and gravel found within the middle water-bearing unit (layer 3).

Continued Artificial Recharge at Linden Ponds

In this alternative, the 1982–96 artificial-recharge pattern for Linden Ponds was repeated twice to simulate the period 1997–2027. The water-level response in selected wells to the repeated 1982–96 recharge pattern (pattern 1, table 13) at Linden Ponds through 2027 is shown in figure 33. Model-simulated water levels in cluster wells northeast of the unnamed fault and southeast of Barrier J (1N/5W-21K3, 1N/5W-22N5, 1N/5W-35B3), and in production well (1S/4W-7C1) southeast of Barrier J, fluctuated in response to the temporal variability in the recharge pattern and the quantity recharged. Simulated water levels in wells 1N/5W-21K3, 1N/5W-22N5, 1N/5W-35B3, and 1S/4W-7C1 rose to their maximum level about 8 years after the onset of the first year of nonzero recharge. Water levels rose by as much as 75 ft in wells 1N/5W-22N5 and 1N/5W-21K3, as much as 50 ft in well 1N/5W-35B3, and as much as 30 ft in well 1S/4W-7C1. Because in the model simulation the imported water is injected directly into layer 3, and not placed on top, the simulated rise in water levels is a lateral pressure transfer that occurs as the injected water displaces the native ground water.

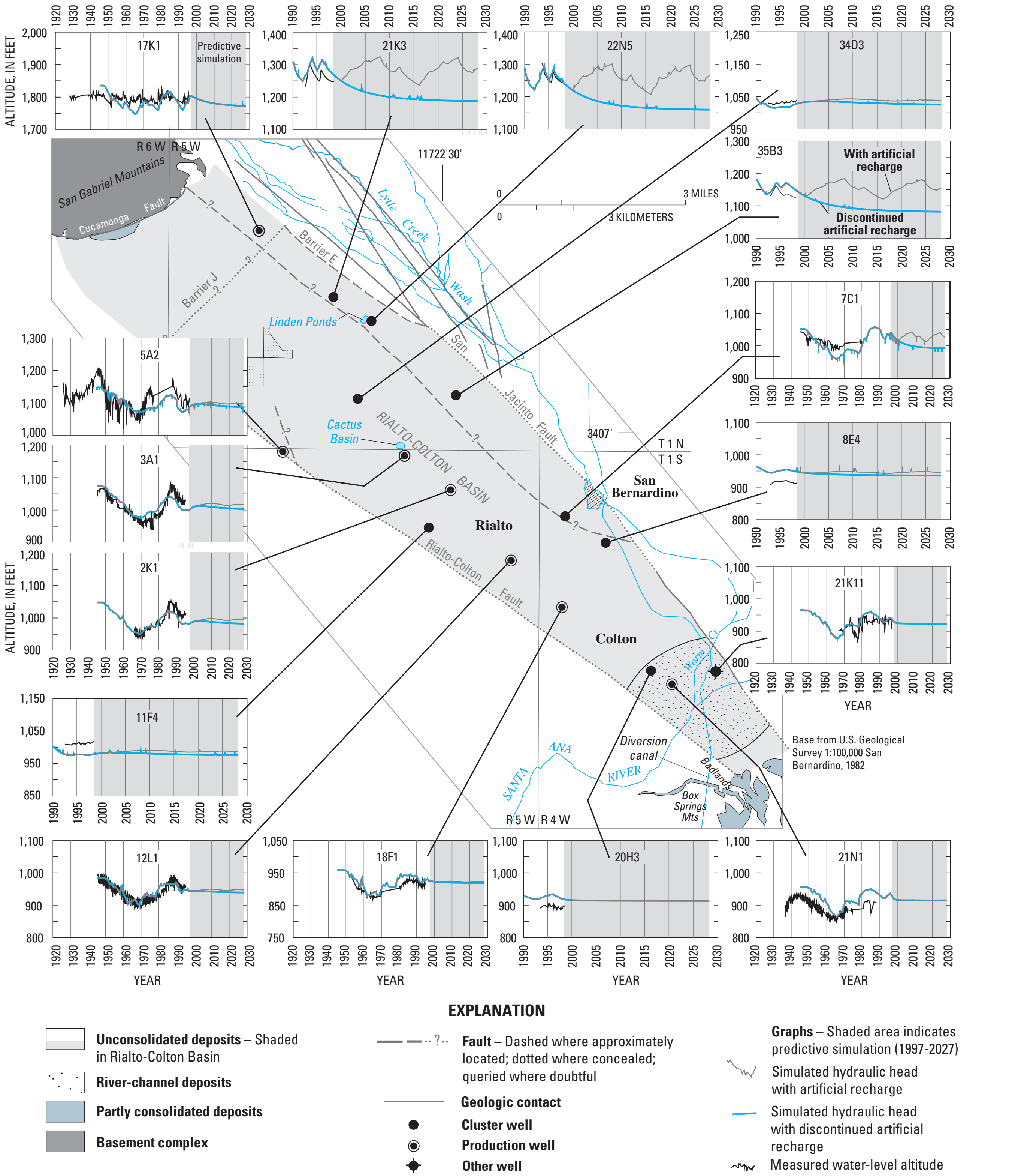

Figure 33. Location of wells, and hydrographs showing measured water-level altitudes and simulated hydraulic-head response in layer 3 for recharge in Linden Ponds, using the 1982–96 recharge pattern and the discontinued artificial-recharge pattern, in the Rialto–Colton Basin, San Bernardino County, California.

Simulated water levels with artificial recharge at Linden Ponds approximated simulated water levels with discontinued recharge in well 1N/15W-17K1 northwest of barrier J, indicating that well is sufficiently isolated by faults to respond to artificial recharge. Model-simulated water levels rose slightly during 1997–2027 in wells 1S/5W-5A2, 1S/5W-3A1, 1S/5W-2K1, 1N/5W-34D3, 1S/5W-11F4, and 1S/4W-18F1. The magnitude of the simulated water-level rises decreases from northwest to southeast as the distance from Linden Ponds increases. A slight response that mimics the pattern of artificial recharge can be seen in the simulated water levels in these wells and simulated water levels rose as much 10 ft after the onset of artificial recharge. Simulated water levels in wells near the Santa Ana River and Warm Creek (1S/4W-21N1, 1S/4W-20H3, and 1S/4W-21K11) do not respond to artificial recharge and approximates water levels with discontinued recharge in the basin.

For the MODPATH simulation of recharge pattern 1 at Linden Ponds, particles were placed in the center of the two model cells containing Linden Ponds (fig. 16); the model then calculated the direction in which these particles (representing the imported water) moved and the distance traveled at the end of the predictive simulation. The flow direction of imported water recharged at Linden Ponds in 1982 using recharge pattern 1 is shown in figure 34. Also shown is the distance traveled (about 5 mi) by the end of the predictive simulation (2027) by the imported water recharged in 1982. The movement of the imported water is southeastward and is largely restricted to the narrow corridor between the unnamed fault and the San Jacinto Fault, and nearly reaches the southeastern segment of the unnamed fault. One flow line did cross the unnamed fault in the vicinity of well 1S/5W-2C1. None of the imported water particles recharged in 1982 reached the outflow boundary between the Rialto–Colton Basin and the Chino and North Riverside Basins and no particles were captured by wells. The average flow velocity of the imported water was about 900 ft/yr.

Discontinued Artificial Recharge at Linden Ponds

Results of the particle-tracking simulation for artificial recharge in Linden Ponds during 1982–96 are shown in figure 35; particle tracking depicted in figure 35*A* begins in 1982 and ends in 1993. The simulation shows (fig. 35*A*) that the imported water recharged in 1982 remains in the narrow corridor between the unnamed fault and the San Jacinto Fault, and just reaches well 1N/5W-26L1, about 1.5 mi southeast of Linden Ponds. The average velocity of imported-water movement was about 600 ft/yr. Imported water did not cross the unnamed fault and reach well 1N/5W-27D2, which was reported to contain imported water in 1993 (Woolfenden, 1994), because the model does not simulate the unfaulted part of the alluvium that allows the movement of imported water to that well.

Imported water was recharged in Linden Ponds during 1982–93. Results of the particle-tracking simulation for artificial recharge in Linden Ponds assuming discontinued recharge (recharge pattern 2) at Linden Ponds during 1997–2027 are shown in figure 35*B*. In figure 35*B*, particle tracking begins in 1982 and ends in 2027. The movement of the imported water (fig. 35*B*) is southeastward along the axis of the basin and is primarily restricted to the narrow corridor between the unnamed fault and the San Jacinto Fault. No flow lines crossed the unnamed fault and no imported water was captured by wells. The imported water moved about 4 mi southeast of Linden Ponds at an average velocity of 700 ft/yr.

Artificial Recharge at Cactus Basin

Results of the simulations for Cactus Basin showing the water-level response to recharge pattern 1, with artificial recharge starting in 2000 and the simulation ending in 2027, are shown in figure 36. Model-simulated water levels in well 1N/5W-17K1 northwest of Barrier J steadily rose during 1997–2027, but as in the previous case, only in response to natural recharge. Again, simulated water levels in well 1N/5W-17K1 matched those of discontinued recharge. Simulated water levels in wells 1N/5W-21K3, 1N/5W-22N5, 1N/5W-35B3, and 1S/4W-7C1 southeast of Barrier J and northeast of the unnamed fault declined slightly, then flattened to a constant level during most of the simulation using recharge pattern 1. Simulated water levels did not respond to the increases and decreases of the pattern of artificial recharge, indicating the influence of the isolating effect of Barrier J and the unnamed fault (fig. 36). Water levels in wells 1S/5W-5A2, 1S/5W-3A1, 1S/5W-2K1, and 1N/5W-34D3 responded to the variations in recharge pattern 1, rising by as much as 50 ft higher than with

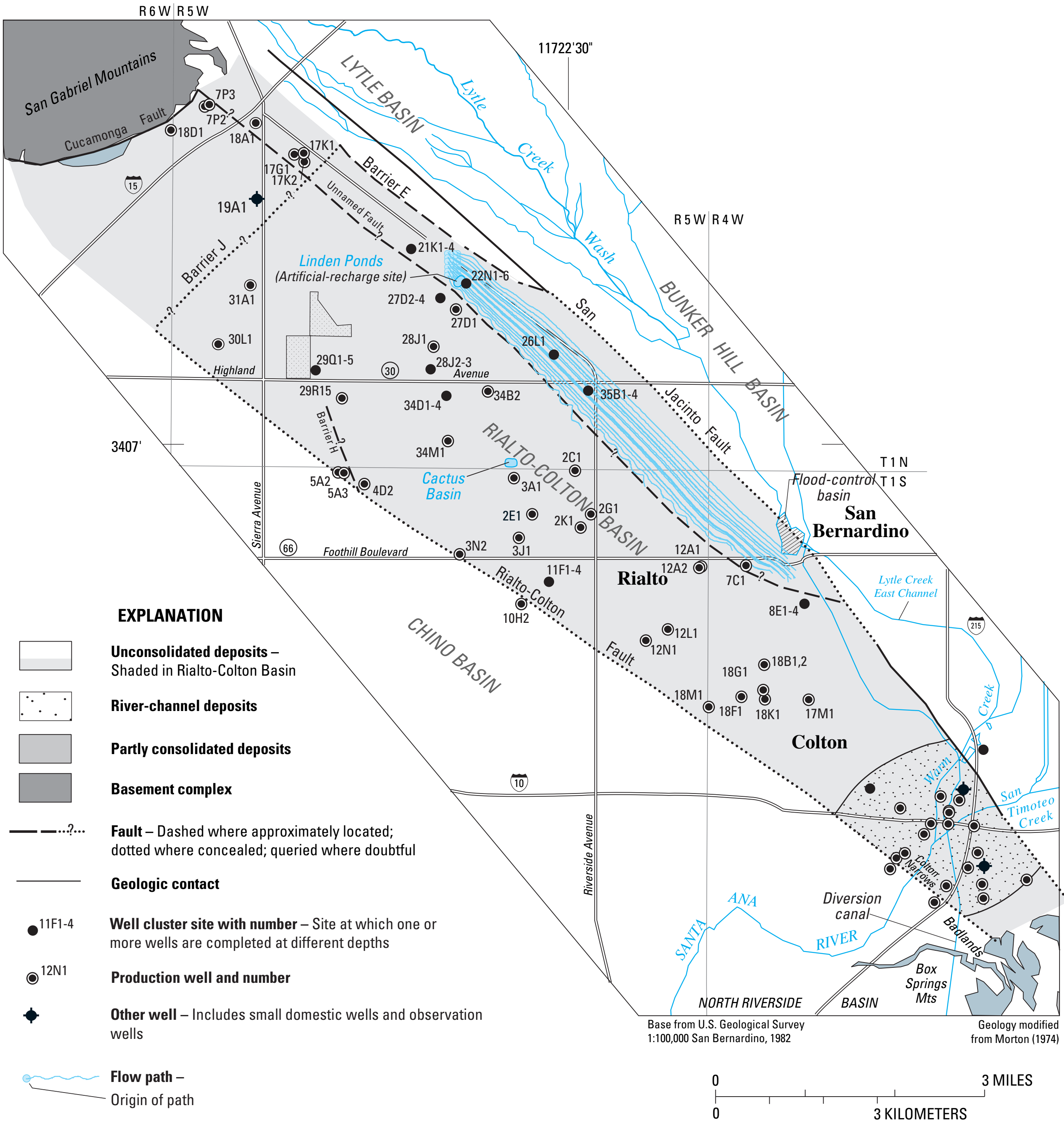

Figure 34. Simulated flow paths of imported water during 1982–2027, with continued recharge at Linden Ponds, using the 1982–96 recharge pattern in the Rialto–Colton Basin, San Bernardino County, California.

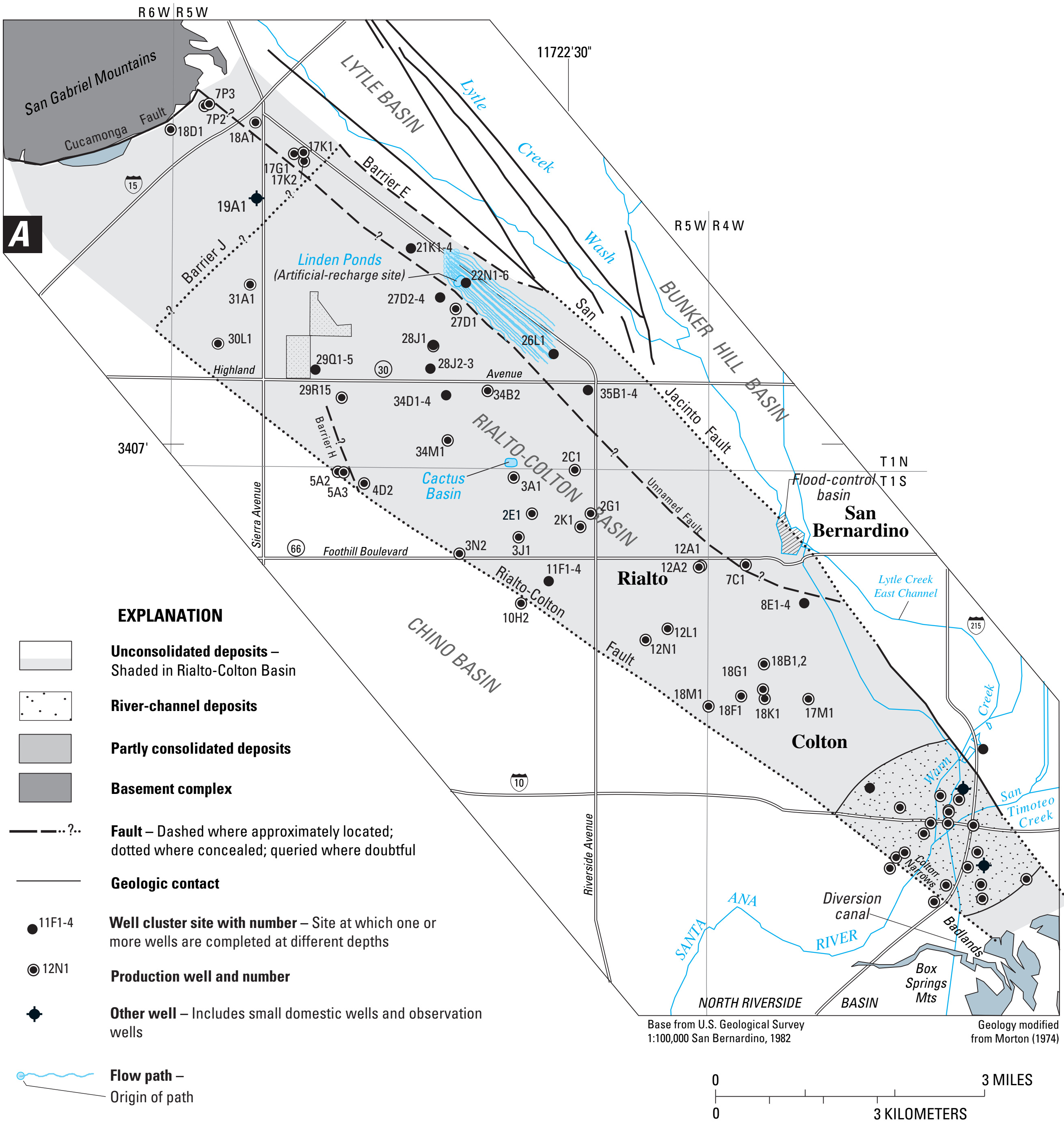

Figure 35. Simulated flow paths of imported water in layer 3 during 1982–93 ***(A)*** and during 1982–2027 ***(B)***, with discontinued recharge at Linden Ponds in the Rialto–Colton Basin, San Bernardino County, California.

Figure 35.—Continued.

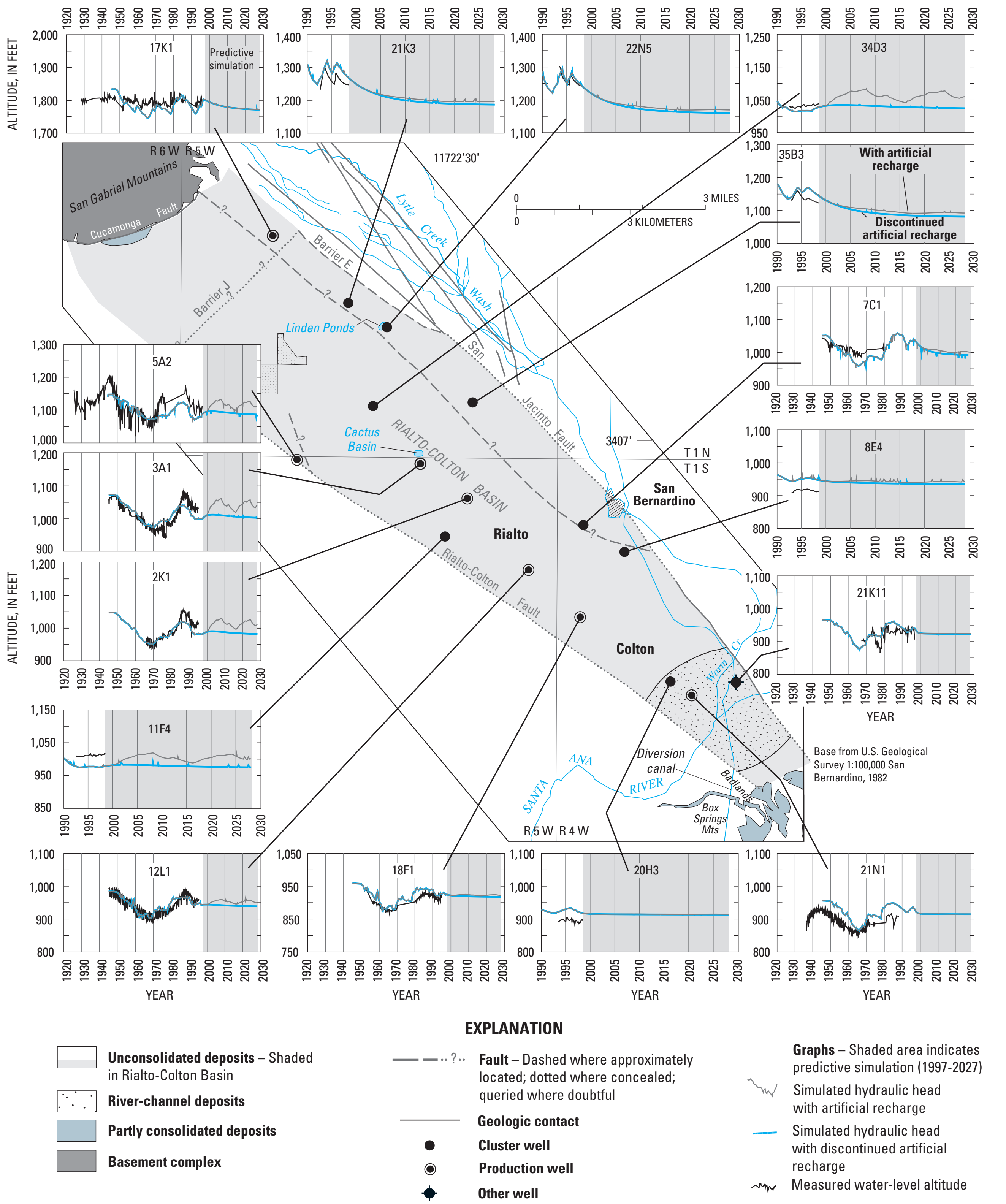

Figure 36. Location of wells, and hydrographs showing measured water-level altitudes and simulated hydraulic-head response in layer 3 for recharge in Cactus Basin, using the 1982–96 recharge pattern and the discontinued artificial-recharge pattern, in the Rialto–Colton Basin, San Bernardino County, California.

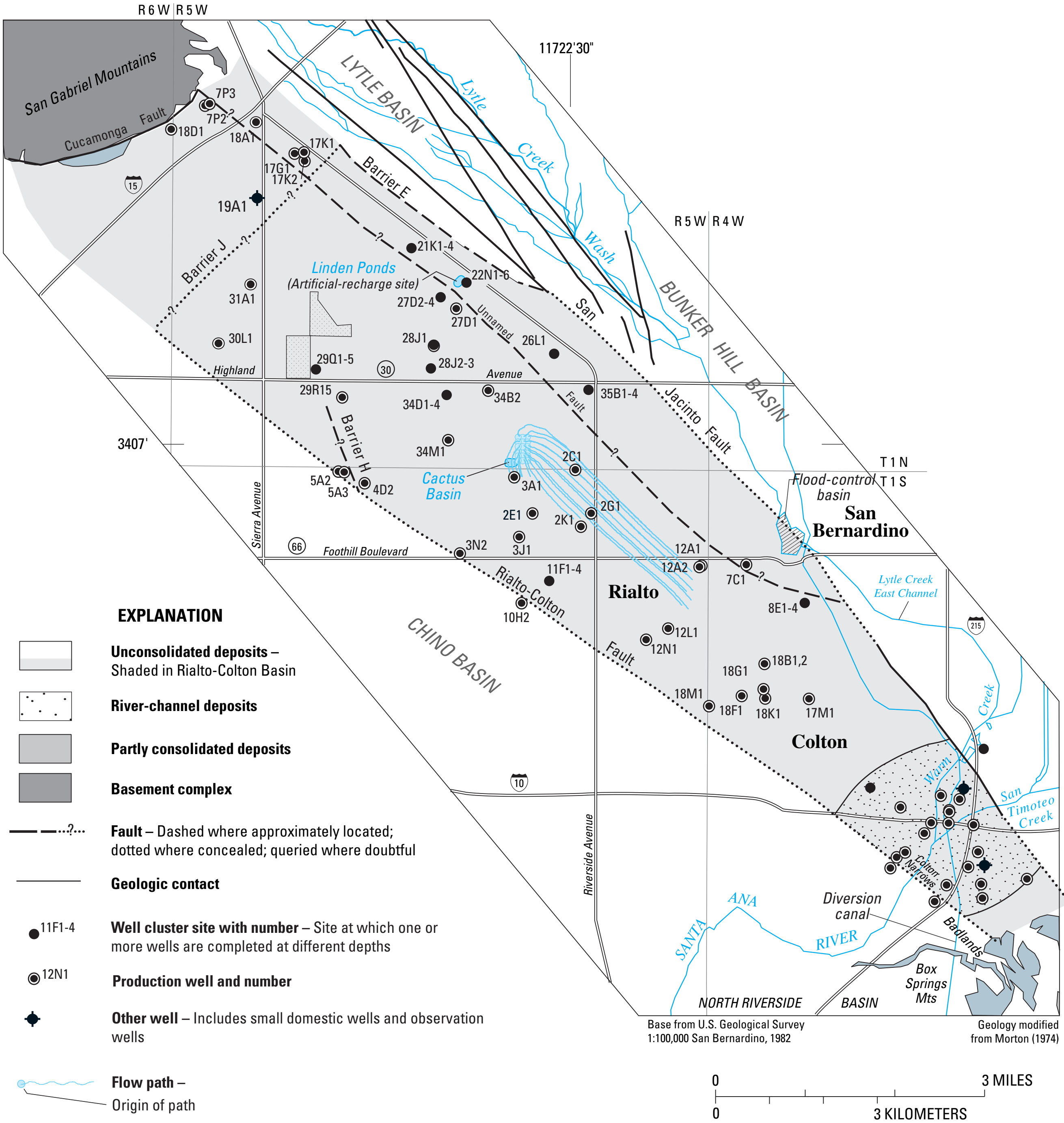

Figure 37. Simulated flow paths of imported water during 2000–2027, with recharge in Cactus Basin using the 1982–96 recharge pattern, in the Rialto–Colton Basin, San Bernardino County, California.

discontinued recharge. Water levels peaked about 7 years after the onset of the first nonzero artificial-recharge year in wells 1S/5W-2K1 and 1S/5W-3A1, and about 8 years after the onset in well 1S/4W-11F4. Water levels in wells 1S/5W-12L1 and 1S/4W-11F4 show a lesser response to recharge pattern 1 in Cactus Basin, rising as much as 20 ft and 25 ft, respectively, higher than the levels with discontinued recharge. Water levels in well 1S/4W-8E4 remained unchanged during the simulation and were about 10 ft higher than water levels with discontinued recharge. Water levels in wells near the Santa Ana River and Warm Creek remained unchanged during 2000–2027 for both artificial recharge and with discontinued recharge patterns, indicating that neither recharge pattern 1 nor natural recharge affects water levels in those wells over the period of this simulation.

Simulated flow paths of imported water recharged in the Cactus Basin during 2000–2027 using recharge pattern 1 are shown in figure 37. Particles were assigned to the cell centers and tracking began in 2000 when recharge was simulated to begin. The imported water is shown to move in a southeastward direction with some lateral movement near the recharge basin. Two wells, 1S/5W-2K1 and 1S/5W-3A1, capture some of the water as indicated by the cessation of flow lines. There also is some movement of imported water upgradient from the recharge basin, owing to a mounding of a large quantity of water. The average flow velocity of the imported water for this recharge alternative is about 500 ft/yr.

DISCUSSION OF RESULTS OF TRANSIENT AND PREDICTIVE SIMULATIONS

Effects of Artificial Recharge and the Importance of the Unnamed Fault

Results of the predictive simulation indicate that artificial recharge in Linden Ponds has little influence on water levels southwest of the unnamed fault but causes water levels to rise significantly in the narrow corridor between the unnamed fault and the San Jacinto Fault. Hydrographs in figures 33 and 36 show that natural recharge under average conditions (1945–96) does not enhance water levels in wells in the corridor between the unnamed fault and the San Jacinto Fault. During the zero-recharge years between artificial-recharge events (2013–2015) at Linden Ponds, water levels in wells responding to artificial recharge declined to the same levels as in earlier zero-recharge years (1995–99), indicating that artificial recharge is the primary source of recharge to those wells during average conditions. Water levels in wells west of the unnamed fault did not respond significantly to artificial recharge in Linden Ponds but showed a steadily increasing trend during 1997–2027, indicating that natural recharge under average conditions influences water levels west of the unnamed fault.

The flow lines from the particle-tracking simulation of discontinued recharge did not extend as far as those of artificial recharge in Linden Ponds. One flow line did cross the central segment of the unnamed fault during the simulation of continued recharge at Linden Ponds. In addition, inspection of figures 34 and 35*B* shows that during the predictive simulation (1997–2027), imported water recharged in 1982 moved about 1.3 mi farther during continued artificial recharge than during discontinued recharge. This indicates that artificial recharge in Linden Ponds has a significant effect on the ground-water flow system within the corridor between the San Jacinto Fault and the unnamed fault when assuming the quantities of recharge used in the predictive simulations. Quantities of imported water artificially recharged in Linden Ponds would need to be increased to move the imported water southwest of the unnamed fault to where the production wells are located.

The unnamed fault creates a flow compartment between it and the San Jacinto Fault. The inability of the model to simulate the movement of imported water southwest of the unnamed fault is a major limitation in addressing the issue of imported-water movement. The particle-tracking simulation should not be used to track imported water recharged in Linden Ponds southwest of the unnamed fault, but it could be used to show flow paths and average flow velocities, qualitatively, in the preferred flow direction along the axis of the basin. Additional data are needed in order to simulate, with confidence, the upper zone of layer 3, in which the unnamed fault is a less restrictive barrier that allows the imported water to move southwestward across the fault and recharge shallow wells (for example, well 1N/5W-27D2 where the imported water was detected in 1993).

Stream Losses from the Santa Ana River and Warm Creek

Seepage from the Santa Ana River and Warm Creek is the third largest source of recharge in the basin. Simulated gains and losses from the Santa Ana River and Warm Creek during 1945–96 are shown in figure 38. During this period, gains to the Santa Ana River and (or) Warm Creek from the aquifer occurred during 1945–50, 1952, 1978, 1981–86, and 1995. Minor quantities (about 11 and 10 acre-ft) of ground water flowed into the Santa Ana River and (or) Warm Creek in 1980 and 1987, respectively. During 1948–96, the Santa Ana River and Warm Creek constantly lost water. The main reason for this constant stream loss is the decline in water levels during the prolonged dry period during 1948–77 and the 6-year drought during 1987–92 in California (fig. 5). Water levels recovered sufficiently to intersect the bottom of the streambed during the 1978–86 wet period. Also, the maximum quantity of stream loss (about 5,500 acre-ft) for many years probably is the maximum value that can be calculated using a streambed conductance of 0.1 ft^2/s.

The average values for the major sources of recharge to and discharge from the Rialto–Colton Basin are given in table 14. During the 1948–77 dry period, seepage loss from the Santa Ana River and Warm Creek (4,619 acre-ft) was slightly less than that

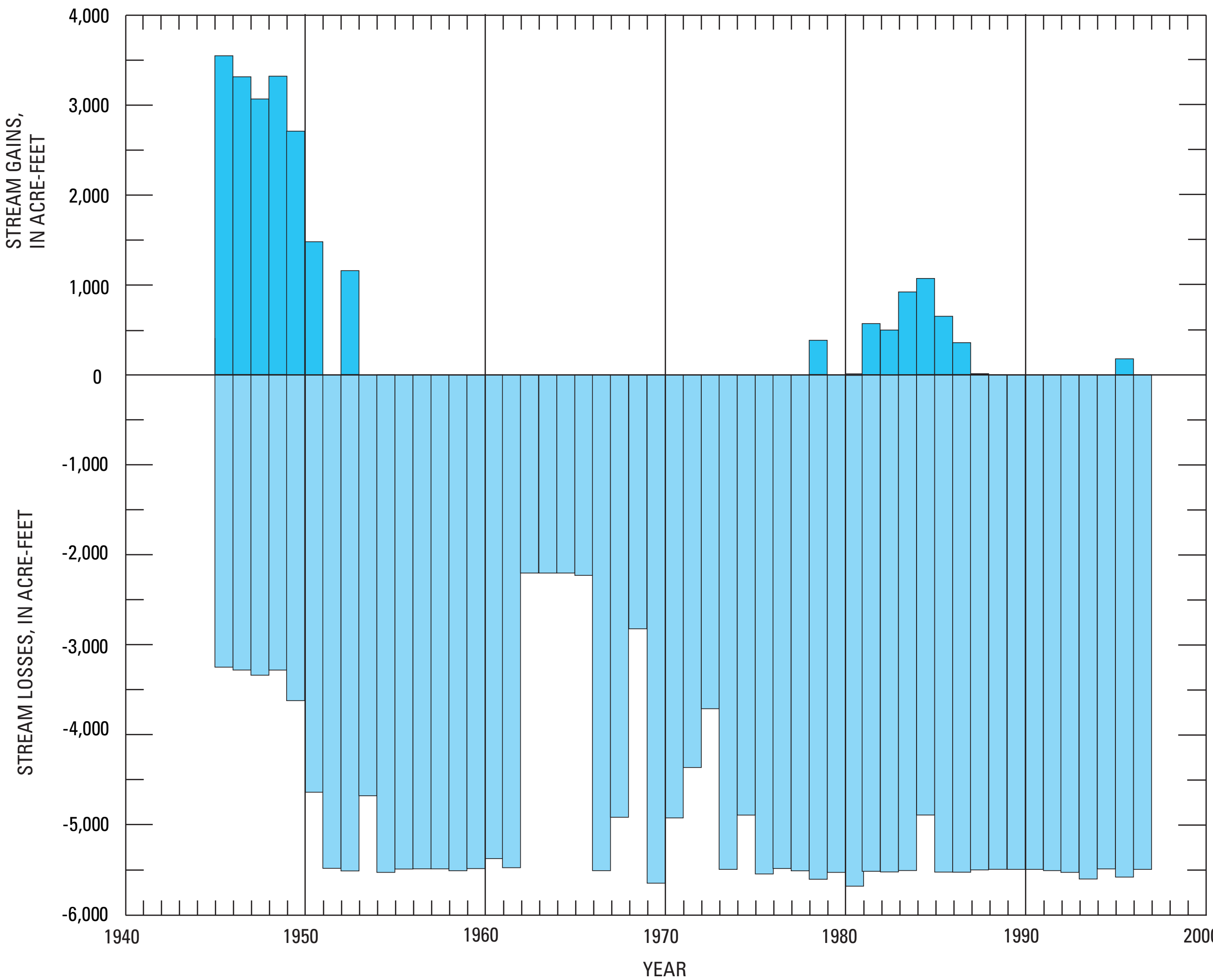

Figure 38. Simulated gains and losses from the Santa Ana River and Warm Creek, 1945–96, in the Rialto–Colton Basin, San Bernardino County, California.

of the 1945–96 average (4,863). After the 1948–77 dry period, water levels in the vicinity of the Santa Ana River and Warm Creek recovered quickly. In 1978, about 380 acre-ft of ground water flowed into the Santa Ana River and (or) Warm Creek along some reaches. Ground water continued to flow into the river and (or) creek every year, except 1979, during 1978–86 wet period. The maximum gain (1,070 acre-ft) during this period occurred in 1984.

The average values in table 14 suggest that the lower water levels are primarily due to increases in pumpage and underflow to the Chino and North Riverside Basins, and a decrease in underflow from the Lytle Basin during the 1948–77 dry period and the 1987–92 drought. A decrease in underflow from the Bunker Hill Basin also contributed to lower water levels during 1987–92. Underflow to the Chino and North Riverside Basins was greater than the long-term average (1945–96) during the 1948–77 dry period; it decreased to below the average during the 1978–86 wet period, and it then increased again during the 1987–92 drought. This is consistent with increased pumping in the Chino and North Riverside Basins, which creates a greater hydraulic gradient toward these basins, thus inducing greater quantities of outflow from the Rialto–Colton Basin. Discharge from pumping in the Rialto–Colton Basin also contributed to the general decline of water levels. Pumpage was slightly greater than the long-term average (11,078 acre-ft) during 1948–77, which was about 31 percent of outflow from the basin. Pumping decreased during the 1978–86 wet period, and then increased to about 1.37 times the long-term average during the 1987–96 drought. Underflow from the Lytle Basin was about 83 percent of the long-term average during 1948–77 and about 73 percent during 1987–92. During the 1978–86 wet period, underflow from the Lytle Basin was about 1.42 times that of the long-term average. Underflow from the Bunker Hill Basin slightly was slightly higher than the long-term average during 1948–77. This is consistent with the increased pumping in the Rialto–Colton Basin that would create greater hydraulic gradients across the San Jacinto Fault. During the 1987–92 drought, underflow from Bunker Hill Basin was about 78 percent that of the long-term average.

Underflow from the Rialto–Colton Basin to the Chino and North Riverside Basins

The long-term (1945–96) average underflow from the Rialto–Colton Basin to the Chino and North Riverside Basins is the main source of discharge from the Rialto–Colton Basin, constituting about 68 percent of total discharge (fig. 32). This is an indication that the Rialto–Colton Basin is not intensely developed (long-term pumpage is 31 percent of total discharge). Under extreme drought conditions and (or) as a result of population growth in the basin, pumpage increases slightly (37 percent of total discharge in 1996). The annual quantities of simulated underflow and net pumpage during 1945–96 are shown in figure 39. During most years of the 1945–96 simulation period, underflow quantities exceeded pumpage quantities by a considerable amount. Pumpage exceeded underflow in ten years during the simulation period, 1958, 1966, 1968–70, 1978, and 1992–95. In 1992, underflow and pumpage were nearly equal. 1969, 1978, 1993, and 1994 were wet years. 1970 and 1995 were dryer years, and water levels remained high, thus maintaining shallower hydraulic gradients across the Rialto–Colton Fault. In 1969 and 1970, pumpage exceeded underflow considerably (by about 10,160 and 8,100 acre-ft, respectively) and was only about 13 percent and 29 percent,

Table 14. Average values of major sources of recharge and discharge in the Rialto–Colton Basin, San Bernardino County, California

[All values are in acre-feet]

Time period	Recharge					Discharge	
	Bunker Hill underflow	Lytle Basin underflow	Seepage loss	Ungaged runoff	Irrigation return flow	Underflow to Chino Basin	Pumpage
1945–96	11,377	8,931	4,863	3,042	3,323	23,746	11,078
1948–77	11,990	7,457	4,619	2,598	3,372	24,956	11,241
1978–86	11,446	12,722	5,475	4,710	2,214	20,580	7,380
1987–92	9,363	6,486	5,500	2,226	4,558	26,007	15,193
1993–96	8,205	13,887	5,539	3,134	4,565	17,520	15,217

respectively, of pumpage. In 1978, there was zero underflow to the Chino and North Riverside Basins. During the 1987–92 statewide drought in California, pumpage in the Rialto–Colton Basin increased, but underflow still was significantly greater until 1991, indicating that pumping in the Chino and North Riverside Basins created hydraulic gradients large enough to induce a considerable quantity of underflow from the Rialto–Colton Basin.

During several years (1958, 1966, 1969, 1970, 1972, 1978, and 1980), simulated underflow from the Chino Basin to the Rialto–Colton Basin occurred along the outflow boundary in some areas. Higher-than-average precipitation occurred during most of these years (1958, 1969, 1978, and 1980), which would produce high water levels. These high water levels could cause either a reversal of the hydraulic gradient toward the Rialto–Colton Basin, creating underflow into the basin from the Chino Basin, or conditions that would cause ground water to flow freely from one basin to the other (Sam Fuller, SBVMWD, oral commun., 2000). Quantities of underflow into the Rialto–Colton Basin ranged from 86 acre-ft in 1966 to 7,543 acre-ft in 1978 (no ground-water outflow occurred during 1978). Precipitation during 1970 was below average; however, water levels probably remained relatively high, thus allowing the reversed hydraulic gradients or freely moving ground-water conditions to be maintained. Precipitation during 1972 was well below average, yet 498 acre-ft of ground water flowed into the Rialto–Colton Basin from the Chino Basin. This implies that either pumpage in the Rialto–Colton Basin near the Santa Ana River exceeded that in the Chino Basin in the same area, thus creating a reversal of gradient, or that the model does not simulate underflow as accurately during this year as during other years.

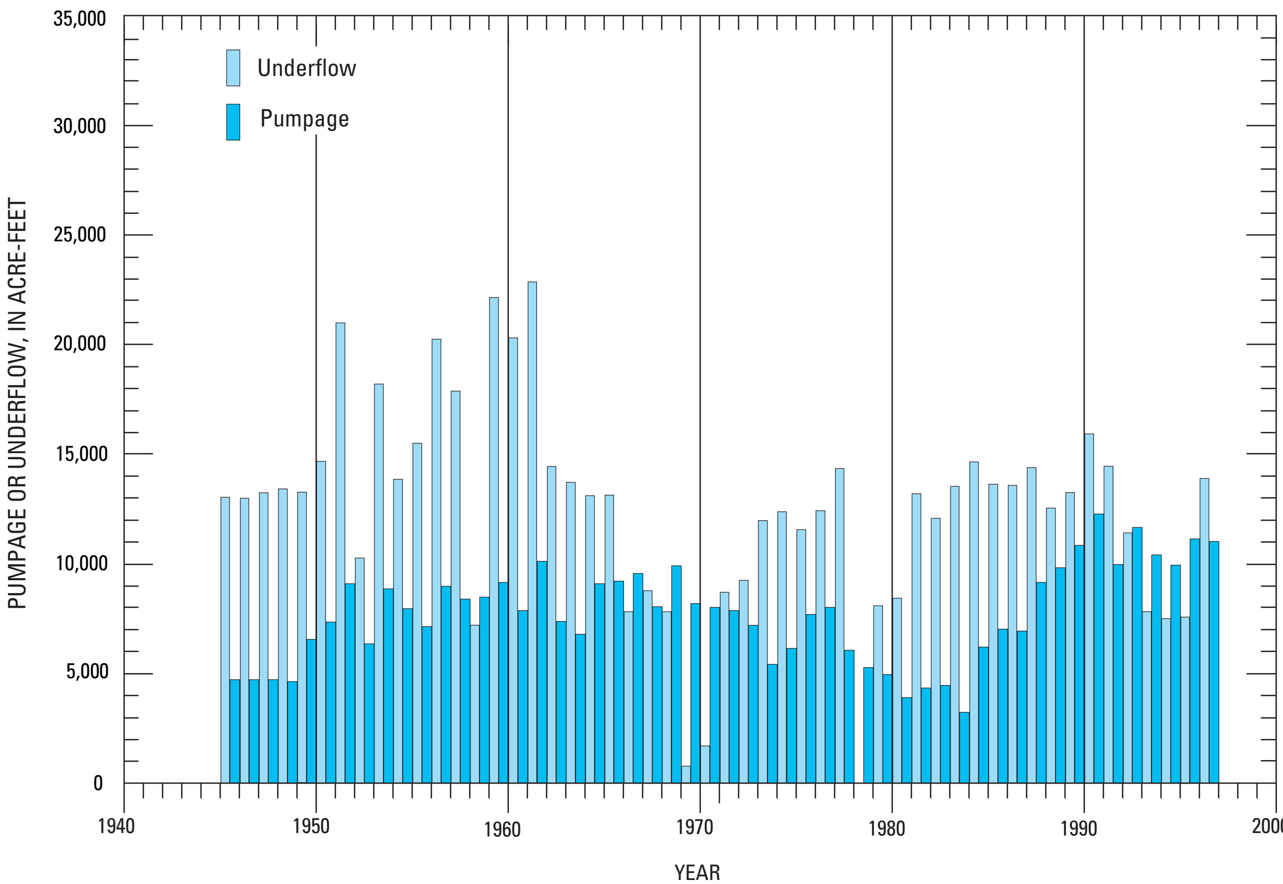

Figure 39. Net pumpage and simulated underflow from the Rialto–Colton Basin to the Chino and North Riverside Basins, 1945–96, San Bernardino County, California.

Underflow from the Lytle Basin to the Rialto–Colton Basin

The simulated quantity of underflow from the Lytle Basin to the Rialto–Colton Basin during 1945–96 is shown in figure 40. With the exception of a few wet years, underflow values for the 30-year dry period during 1948–77 were comparatively small (less than the long-term average of about 8,931 acre-ft). In 1961, underflow from the Lytle Basin was only 31 percent of the long-term average. Average underflow during 1948–77 period was about 7,457 acre-ft (table 14), 16 percent lower than the long-term average. Average underflow during the 1978–86 wet period was 12,722 acre-ft, significantly higher (42 percent) than the long-term average (table 14). During the 1987–92 drought, the average underflow was about 6,486 acre-ft, 73 percent of the long-term average.

Underflow from the Lytle Basin to the Rialto–Colton Basin is influenced by the quantity of discharge in Lytle Creek. Water levels in well 1N/5W-17K1 respond rapidly to streamflow in Lytle Creek, and water sampled from this well was tritiated, indicating recent (less than 50 years old) recharge (Woolfenden and Kadhim, 1997). It should be mentioned, however, that the source of underflow may not be entirely from streamflow in Lytle Creek. The method of using Lytle Creek discharge values to obtain underflow values was simply a way to quantify a largely unknown value. Underflow values from the Lytle Basin to the Rialto–Colton Basin used in the calibrated model of the Bunker Hill and Lytle Basins were held constant during 1945–96 (W.R. Danskin, USGS, written commun, 1999). This method was tried initially in the construction and calibration of the flow model for the Rialto–Colton Basin, but it was quickly evident that underflow

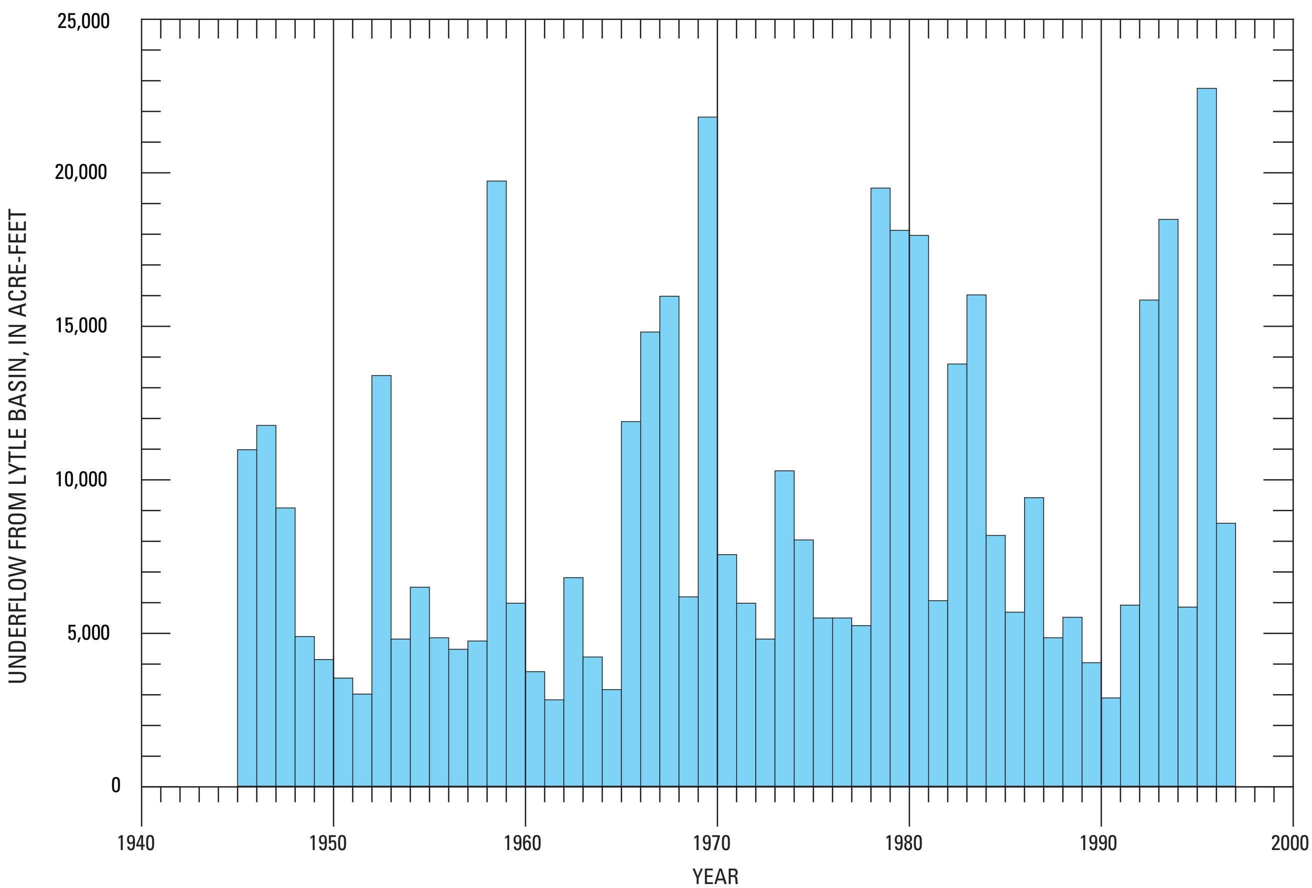

Figure 40. Simulated underflow from the Lytle Basin to the Rialto–Colton Basin, 1945–96, San Bernardino County, California.

from Lytle Basin greatly influences the variability in basinwide water levels.

During model calibration, the quantity of underflow from Lytle Basin was adjusted until simulated water levels matched measured water levels in well 1N/5W-17K1 by multiplying the discharge in Lytle Creek by 35 percent if discharge was less than two standard deviations above the mean annual discharge, and 15 percent if discharge was greater than or equal to two standard deviations above the mean (fig. 41). Two standard deviations above the mean annual discharge is 99,077 acre-ft. In each of the two categories of Lytle Creek discharge, an increase in discharge results in an increase in underflow. Five years (1969, 1978, 1980, 1983, and 1993) of exceptionally high discharge occur in the 15 percent category (fig. 41). It is possible to obtain underflow values during these high-discharge years that are less than those during other years using this method. This result is supported by the calculation of underflow from the Bunker Hill Basin, which was made using hydraulic gradients. During exceptionally wet years such as 1969, 1978, 1980, 1983, and 1993, hydraulic gradients generally were shallower than during normal or dryer years, resulting in smaller quantities of underflow from the Bunker Hill Basin than during other years.

The percent-of-discharge method is one way to base calculation of underflow on real data. It is not necessarily the best method of estimation. Installation of shallow wells in the Lytle Basin and northwestern Rialto–Colton Basin, and long-term water-level monitoring would provide needed data to validate this method or to calculate underflow using a more robust method.

Underflow from the Bunker Hill Basin to the Rialto–Colton Basin

Underflow from the Bunker Hill Basin to the Rialto–Colton Basin is a significant source of recharge. The quantities of underflow initially used in model

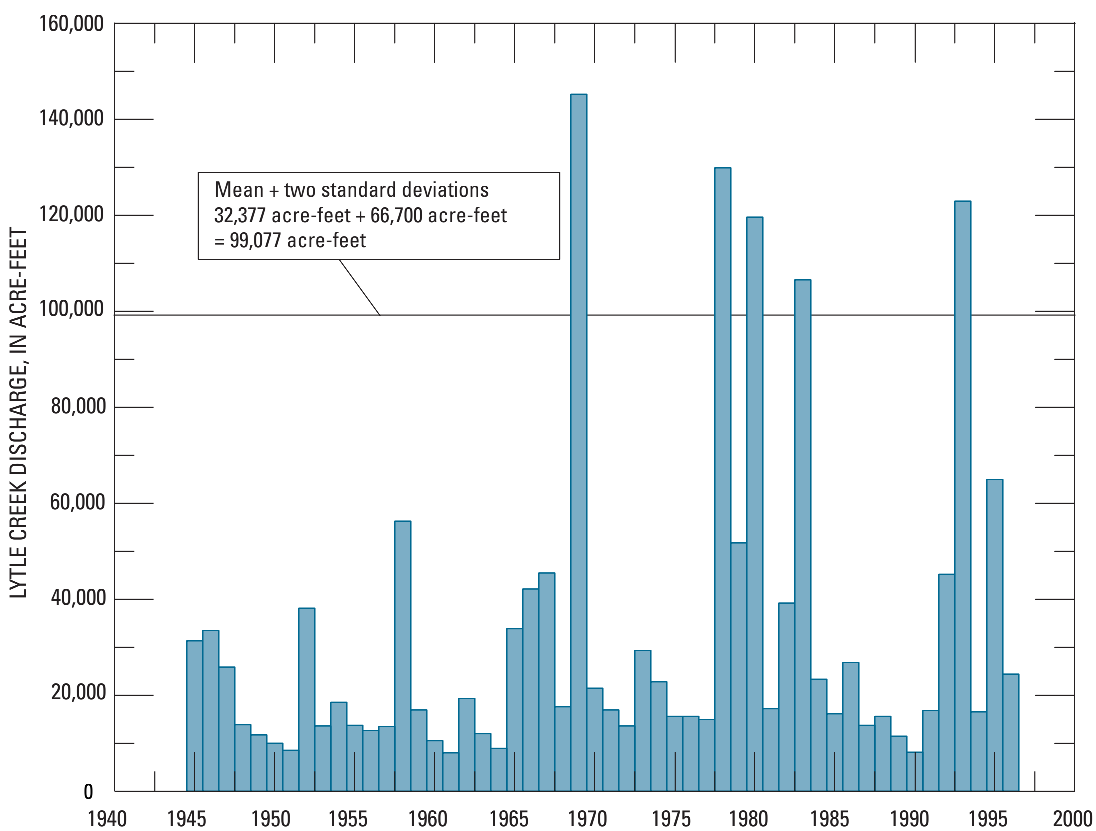

Figure 41. Annual discharge in Lytle Creek, 1945–96, San Bernardino County, California.

construction and calibration were based on a linear-regression relation used in the Bunker Hill and Lytle model (W.R. Danskin, USGS, written commun., 1997). During model calibration, however, the quantities of underflow required adjustment in order to match simulated water levels with measured water levels. Shown in figure 42 are the underflow values used in the Rialto–Colton model.

As mentioned previously (see “Underflow” subsection [“Flow-Model Construction” section]), underflow from the Bunker Hill Basin was based on calculation of Darcy’s Law. These estimates did not follow the same wet- and dry-period trend as did that from the Lytle Basin. During the 1948–77 dry period and the 1978–86 wet period, underflow from the Bunker Hill Basin was not significantly different (greater by about 5 percent and 1 percent, respectively) from that of the long-term average. Pumping during the dry period also was not significantly different (about 2 percent greater) than the long-term average pumping. During the wet period, however, pumping was considerably greater (33 percent) from the long-term average. This indicates that overall decreases in pumping and rises in water-levels the Rialto–Colton Basin during the wet period matched those in the Bunker Hill Basin in order to maintain the overall hydraulic gradients equivalent to those during 1948–77 and, as a result, roughly equivalent values of underflow. During the 1987–92 drought, underflow was only about 82 percent of the long-term average. Pumping in the Rialto–Colton Basin, however, was considerably greater (about 37 percent) than the long-term average. The additional pumping in the Rialto–Colton Basin did not induce greater underflow across the San Jacinto Fault, indicating that water levels in the Bunker Hill Basin had declined sufficiently to decrease the hydraulic gradient across the San Jacinto Fault to less than the long-term average and less than during the previous dry and wet periods. A shallow hydraulic gradient combined with a decline in water levels, and thus, less saturated thickness, results in quantity of underflow smaller than that during the previous dry and wet periods, and smaller than the long-term average.

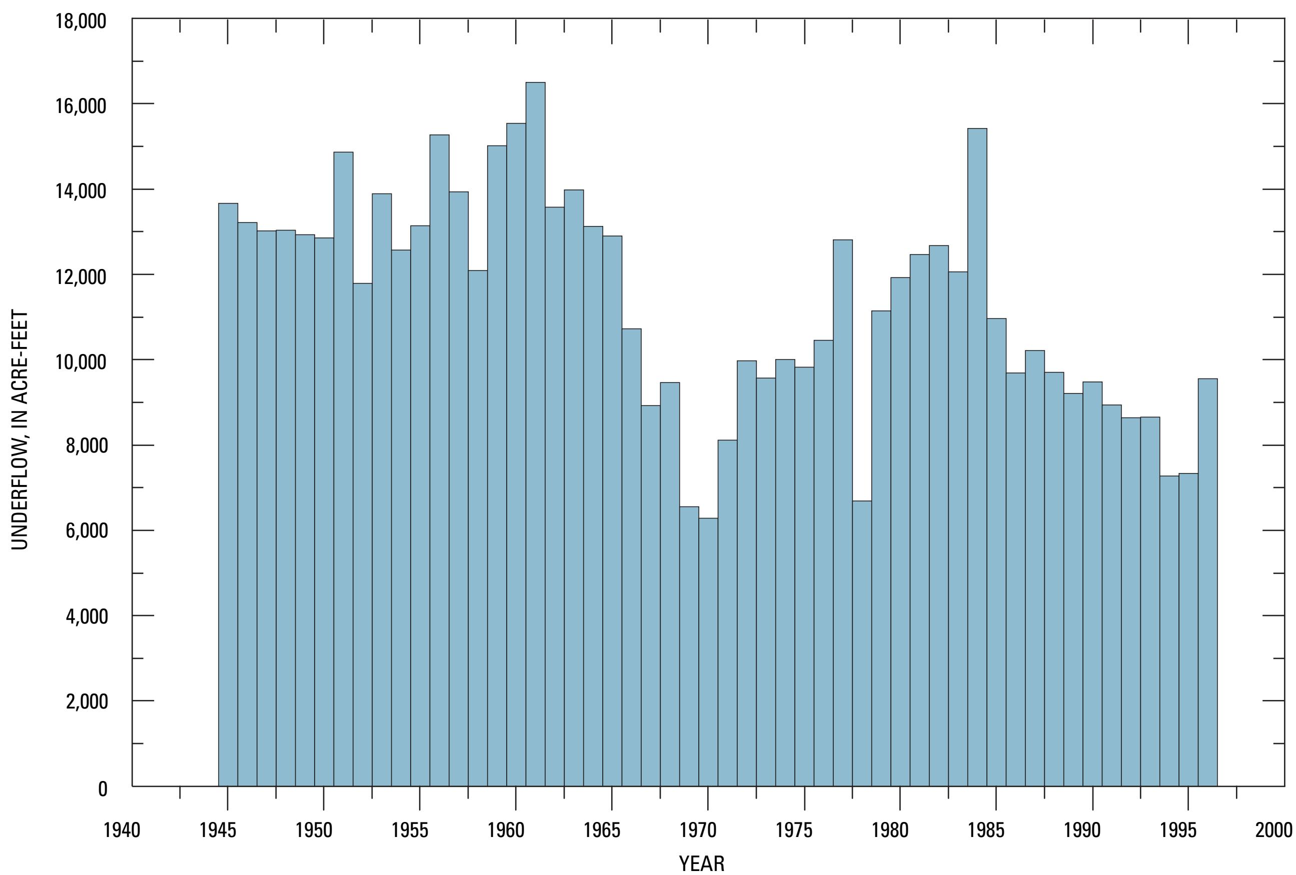

Figure 42. Simulated underflow from the Bunker Hill Basin to the Rialto–Colton Basin, 1945–96, San Bernardino County, California.

USE AND LIMITATIONS OF GROUND-WATER FLOW AND PARTICLE-TRACKING MODELS

The ground-water flow model can best be used as a tool for comprehensively analyzing hydrologic processes in the Rialto–Colton Basin. The model incorporates all available data for the system and calculates quantitative estimates of flows and heads, including their spatial and temporal variations. The model was designed to answer general questions regarding basin-wide ground-water flow directions, to refine the existing conceptual model, and to evaluate boundary conditions, water budgets, and the effects of artificial recharge on the ground-water flow system.

The model also can be used as a guide for future data collection. For example, the inability of the model to simulate the flow of imported water across the unnamed fault during 1982–93 points to the need for collection of data in the upper part of layer 3, where the imported water probably occurs. Definition of the location and extent of the unnamed fault both laterally and vertically with surface geophysics, drilling of shallow wells, collection of water-chemistry data, and long-term water-level monitoring would lend confidence to a finer vertical discretization of layer 3 in the vicinity of the artificial-recharge ponds. Another example of using the model as a guide to direct future data collection is the need to collect seepage data along the Santa Ana River and Warm Creek. These data would provide additional calibration targets that would help further constrain the model; they also would help in assessing the estimated quantities of underflow from the Bunker Hill Basin to the Rialto–Colton Basin and model-calculated quantities of underflow from the Rialto–Colton Basin to the Chino and North Riverside Basins.

Although a ground-water model can be a useful tool for investigating aquifer response, it is a simplified approximation of the actual system based on average or estimated conditions, and the accuracy of its predictions are dependent on the accuracy of the input data. The flow model has been calibrated to observed long-term and short-term trends of hydraulic heads throughout the basin. Deviation of simulated hydraulic heads from measured water levels results from simplifications associated with the system conceptualization; errors in estimated aquifer characteristics and model parameters; errors of estimated or measured recharge, discharge, or historical water levels; and errors associated with the numerical-solution procedure.

During the course of model calibration, adjustments to the conceptual model could be required in order to match water levels adequately. Generally, the numerical model can be a useful tool in understanding a ground-water flow system. However, data are not areally extensive enough to provide a completely accurate determination of physical features. In this study, flow barriers were reoriented and extended to better simulate elevated water levels in given areas. In addition, initial estimates of bottom altitudes of model layers were decreased by as much as 400 ft immediately southwest of Barrier J to represent altitudes based on historical data and to prevent the drying of model cells where the water levels were known not to have declined below a given water-bearing unit (model layer).

Simplifications described in the flow model "Assumptions" section of this report can contribute to errors that might affect the model's accuracy. Simplifications include representing the middle water-bearing unit as one layer. The middle water-bearing unit consists of two zones: an upper zone that can contain perched water (a saturated zone not connected to the main aquifer owing to its location overlying a low-permeability layer) and a lower zone that is the main water-producing zone in the basin. Because few water-level data are available for the upper zone and the areal extent of the clay lens separating the zones is not well known, the upper zone was not simulated as a separate layer. The upper zone, however, is important because the imported water probably has moved, to date, only in this zone. Another simplification is that layer 3 is the only active layer occurring northwest of Barrier J. Few subsurface data exist northwest of Barrier J. The presence of layer 3 northwest of Barrier J is based on the chemistry of the water in well 1N/5W-17K1 (Woolfenden and Kadhim, 1997), which is consistent with that of the water in wells perforated in the middle water-bearing unit southeast of Barrier J and southwest of the unnamed fault.

The assumption of no-flow boundary conditions along most of the San Jacinto Fault and the Rialto–Colton Fault also may contribute to errors. Ground water may flow in the unfaulted part of the alluvium from the Bunker Hill Basin to the Rialto–Colton Basin over the top of the San Jacinto Fault and from the Rialto–Colton Basin to the Chino Basin over the top of the Rialto–Colton Fault. Other simplifications include the simulation of clay lenses with a vertical-conductance value instead of a separate layer; an assumption of homogeneity of the layers where there may be heterogeneities within the basin that are currently (1999) unknown; and the assumption of an absence of faults southeast of Barrier J and west of the unnamed fault where faults may exist. The simplification of using a constant 30-percent irrigation-return-flow factor for the entire transient simulation period (1945–96) also could have a significant effect on model results. Future work should include a variable return-flow factor to account for changes in land use from agricultural (higher return flow) to urban (lower return flow).

The method for accounting for irrigation return flow assumes that irrigation return occurs immediately; whereas, in areas where there is a thick unsaturated zone (such as in the Rialto–Colton Basin), return flow may take years to reach the water table. This delay could have a significant effect on timing of actual water-level declines and recoveries.

There are limitations and errors specific to the use of horizontal-flow barriers in simulating faults internal to the Rialto–Colton Basin. These limitations and errors include uncertainty as to the degree of hydraulic connection between the fault-bounded compartments within the basin, the fact that the model does not account for storage effects in the horizontal-flow barriers, and the uncertainty of the estimated hydraulic characteristic assigned to each barrier. Errors in the number, location, and estimated hydraulic characteristics of the horizontal-flow barriers can affect both initial-conditions and transient simulations. Errors introduced by omission of the storage properties of the barriers will be manifested only during transient simulations.

Recharge, discharge, and water levels generally are considered to have been measured or estimated correctly. However, errors in these values can be a serious concern because they directly affect model values of aquifer characteristics and (or) model parameters. For example, inaccuracies in water-level measurements that are used in model calibration can directly affect the model value obtained through model calibration. The quantity of underflow from the Lytle Basin was determined by increasing or decreasing estimates until simulated head approximated measured water-level altitudes at well 1N/5W-17K1. If actual water-level measurements for well 1N/5W-17K1 were higher or lower than those used, different values of underflow would have been obtained. Thus, a greater certainty in the values of one input will generally translate into a lessening of the uncertainty in the values of the other.

The numerical model is based on the "ground-water flow" equation, which is an approximation used to characterize ground-water flow systems, and the equation describes the time-varying hydraulic-head configuration in three dimensions for ground water of constant density in a porous medium. The equation takes into account major influence factors and neglects others. Analytical solutions to the ground-water flow equation are valid through continuous space and time intervals, but solutions to the equations used in the numerical model (approximations to the ground-water flow equation) are valid only at discrete locations at specified times. The numerical model can calculate flow rates from the hydraulic-head information it generates, but they are not a direct solution result.

As the number of model-grid cells is increased and the length of model stress periods is reduced, results calculated by the numerical model will approach the exact solution to the ground-water flow equation. In general, the numerical model is an approximation, but experience has shown that it is a good one. Nonetheless, a certain amount of error is introduced by these approximations. Additional error is introduced by assuming that hydraulic conductivity and specific storage (or storage coefficient) are strictly functions of location and not of both location and time. Other errors result from truncation of numeric values or selection of convergence criterion or are associated with the particular numerical procedure used to solve the model equations. Usually, these errors are not serious.

Care should be used in interpreting model results where the model is poorly calibrated, such as near Barrier H and in the vicinity of well 1N/5W-27D1, or where available data are sparse, such as northwest of Barrier J. Poorly calibrated parts of the model reflect site-specific inaccuracies in conceptualization of the ground-water flow system owing to lack of information; significant errors can be introduced where few data are available.

Limitations specific to the MODPATH simulations include those associated with discretization and those associated with uncertainty of parameters and boundary conditions. The degree of spatial discretization influences the level of detail at which hydrogeologic and system boundaries can be represented, the accuracy of velocity calculations, and the ability to accurately and unambiguously represent internal sinks

(Pollock, 1994). The discretization of the Rialto–Colton model represents the hydrogeologic and system boundaries with adequate accuracy. The constant grid spacing of the Rialto–Colton model introduces error in the velocity calculations near strong sources or sinks. Where the model grid contains a strong source or sink, such as near the recharge ponds or large production wells, finer discretization in the vicinity of the source or sink would produce more accurate calculations of velocity. The effect of spatial discretization on the representation of internal sinks is especially important for particle-tracking analyses because of the ambiguity associated with the movement of particles through weak sink cells. These cells contain sinks that do not discharge at a large enough rate to consume all of the water entering the cell (Pollock, 1994). Although it was assumed that some of the particles would pass through cells with weak sinks, there is no way to know whether a specific particle should discharge to the sink or pass through it. The uncertainty associated with this limitation, however, may not be large because of the lack of production wells in the direction of flow of imported water from the artificial-recharge ponds.

The uncertainty in parameters and boundary conditions is the most important limitation in both the ground-water-flow and particle-tracking analyses. The use of estimated values of aquifer characteristics (such as hydraulic conductivity, storage coefficient, and vertical hydraulic conductivity) and model parameters (conductance of the general-head boundary between the Rialto–Colton Basin and the Chino and North Riverside Basins and the fault hydraulic characteristics) will introduce error into the model. These errors are difficult to quantify because both aquifer characteristics and model parameters were obtained, for the most part, through model calibration. The uncertainty of the location of the Rialto–Colton Fault boundary also will introduce error into the model. Uncertainty associated with aquifer characteristics may be relatively small because, overall, the model is not as sensitive to aquifer characteristics as it is to the model parameters. Uncertainty in the numerical representation of boundary conditions requires that interpreting model results near boundaries should be done with care.

As mentioned previously in the “Simulated Effects of Artificial-Recharge Alternatives on Ground-Water Levels and Movement” section, imported-water particles in the MODPATH simulations did not reach well 1N/5W-27D2 in 1993 (fig. 35*A*). However, imported water was presumed to be detected in that well in 1993 on the basis of stable-isotope data (oxygen-18 and deuterium) collected for Phase 1 of this study (Woolfenden, 1994). The current conceptualization of the ground-water flow system, which is based on available geohydrologic data, does not account for a mechanism that would allow significant quantities of water to move across the unnamed fault in layer 3, and thus be detectable at well 1N/5W-27D2. A clay lens separates the middle water-bearing unit (layer 3) into two zones near the Linden Ponds artificial-recharge site, and the imported water probably moves across the unnamed fault in the upper zone of this unit where the fault may be a less restrictive barrier. Hence, results of the ground-water flow model and the particle-tracking model, in this regard, demonstrate the applicability of collecting and analyzing additional data, such as those that can be obtained from drilling relatively shallow test-monitoring wells and performing aquifer tests (which were beyond the scope of this study). These data would refine the conceptual and mathematical models of the Rialto–Colton ground-water basin. Nonetheless, it is believed that, in general, the current models offer valuable insight into the gross behavior of the ground-water flow system and the movement of imported water.

SUMMARY AND CONCLUSIONS

The Rialto–Colton Basin trends northwest-southeast; its width is about 3.5 mi in the northwest and about 1 mi in the southeast, and its length is about 10 mi. The basin is bounded on the northeast by the San Jacinto Fault and on the southwest by the Rialto–Colton Fault. The San Gabriel Mountains and the Badlands form the northwestern and southeastern boundaries, respectively. Consolidated deposits underlie the basin and form its lower boundary. Ground-water movement is from east to west in the river-channel deposits; from northwest to southeast and from east to west in the upper water-bearing unit; and along the axis of the basin from northwest to southeast in the middle and lower water-bearing units. Three internal barriers—Barrier J, Barrier H, and an unnamed fault—restrict ground-water movement to various degrees within the Rialto–Colton Basin. The location and extent of Barrier H and the unnamed fault were modified during model calibration.

The ground-water flow system in the Rialto–Colton Basin consists of unconsolidated and partly consolidated deposits of gravel, sand, silt, and clay. The ground-water flow system is divided into four water-bearing units: the river-channel deposits, and the upper, middle, and lower water-bearing units. Thickness of the water-bearing units varies within the basin. Thickness of the middle water-bearing unit, which is the main water-producing unit in the basin, ranges from about 240 to 600 ft.

Sources of recharge to the Rialto–Colton Basin are underflow from the Lytle and Bunker Hill Basins; seepage loss from the Santa Ana River, Warm Creek, and the diversion canal; surface spreading of imported water; ungaged runoff from the San Gabriel Mountains and the Badlands, and subsurface inflow; irrigation return flow; and areal recharge of rainfall. The components of discharge from the Rialto–Colton Basin are pumpage, underflow from the Rialto–Colton Basin to the Chino and North Riverside Basins, seepage loss from the aquifer to the Santa Ana River and Warm Creek, and evapotranspiration.

A three-dimensional finite-difference model, MODFLOW, was used to simulate and evaluate ground-water flow in the Rialto–Colton Basin. The ground-water flow system was divided into four layers that represent the river-channel deposits, and the upper, middle, and lower water-bearing units. A particle-tracking model, MODPATH, was used to simulate advective transport of imported water within the flow system for three artificial-recharge alternatives.

The flow model was calibrated to transient conditions for 1945–96. A simulation was made to provide initial conditions for the transient-state simulation by using 1945 recharge and discharge rates, and assuming no change in storage. For the initial conditions, the model-simulated hydraulic heads generally matched measured water levels more closely in wells in the central and southeastern parts of the basin than in other parts of the basin. For transient conditions, the model-simulated hydraulic heads generally matched water levels more closely in wells northwest of Barrier J, in the northwestern part of the basin just southeast of Barrier J during 1982–96, and in the central part of the basin during 1945–82. In addition, water levels were matched adequately east of the unnamed fault during the transient simulation.

Total recharge in 1945 was about 34,920 acre-ft for the initial-conditions simulation. Combined underflow from the Bunker Hill and Lytle Basins accounted for about 70 percent of recharge to the basin in 1945 for the initial-conditions simulation. Seepage loss accounted for about 9 percent in 1945 for the initial conditions. Total discharge for 1945 initial conditions was 34,940 acre-ft. Underflow from the Rialto–Colton Basin to the Chino and North Riverside Basins accounted for about 71 percent of total discharge, and pumpage accounted for about 19 percent.

Average total recharge for the 1945–96 transient simulation was 33,620 acre-ft. Average total discharge was 35,220 acre-ft, indicating that, for longer periods, overdraft conditions may exist but are not significant (about 5 percent of average total recharge). Underflow from the Bunker Hill and Lytle Basins accounted for about 60 percent of total recharge. Seepage loss from the Santa Ana River and Warm Creek accounted for about 15 percent of total recharge. During 1945–96, an average of 7,350 acre-ft of water was removed from storage and an average of 5,960 acre-ft of water went into storage. Underflow to the Chino and North Riverside Basins accounted for about 68 percent of total discharge. The net average storage depletion was about 1,390 acre-ft/yr.

Total recharge for the 1996 transient simulation was 31,830 acre-ft and total discharge was 42,200 acre-ft. The net average reduction in storage (net average recharge minus net average discharge) was 10,370 acre-ft/yr. Underflow from the Lytle and Bunker Hill Basins accounted for about 58 percent of total recharge. Seepage loss from the Santa Ana River and Warm Creek accounted for about 18 percent of total recharge. Pumpage and underflow from the Rialto–Colton Basin to the Chino and North Riverside Basins were higher than the 1945–96 averages. The quantity of water coming out of storage was 11,110 acre-ft and the quantity of water going into storage was 720 acre-ft. Storage depletion was 10,390 acre-ft.

A sensitivity analysis was done to determine the model inputs that were most important in affecting model-generated hydraulic heads at the calibration wells. In addition, considerable calibration effort was placed on determining reasonable values for those items that were both the most sensitive and least well known. In layers 1, 2 and 3, hydraulic heads were most sensitive to an increase in total recharge. Hydraulic heads in layer 1 also are sensitive to an increase in the streambed conductance. Hydraulic heads in layers 2 and 3 also are sensitive to removal of all internal barrier conditions. In layer 4, hydraulic heads were most sensitive to the removal of all internal barriers and removal of the unnamed fault. Hydraulic heads were least sensitive in layer 1 to a reduction in the primary storage coefficient and the removal of Barrier H; in layer 2, to an increase in the primary storage coefficient and the removal of Barrier H; in layer 3, to a decrease in the primary storage coefficient and an increase in the vertical conductance; and in layer 4 to an increase in the primary storage coefficient and a decrease in the primary storage coefficient.

The goal of artificial recharge in the Rialto–Colton Basin is to store imported water during wet periods for use during dry periods. To achieve this goal, it is desirable for the imported water to be available to production wells within the basin. Predictive simulations were made for three artificial-recharge alternatives: continued artificial recharge at Linden Ponds, discontinued artificial recharge in the Rialto–Colton Basin, and artificial recharge at Cactus Basin. To extend the ground-water flow model beyond 1996, average hydrologic conditions (natural recharge and discharge) for 1945–96 were used for the predictive simulation period (1997–2027). Two recharge patterns were evaluated for the artificial-recharge alternatives: using the 1982–94 recharge quantities in Linden Ponds (pattern 1) and discontinuing recharge at Linden Ponds (zero recharge, pattern 2). Years of zero recharge were included between the 13-year periods of recharge for pattern 1. Particle-tracking simulations were made for all three artificial-recharge alternatives. For recharge at Linden Ponds, particle tracking began in 1982. For recharge at Cactus Basin, particle tracking began in 2000.

For continued recharge at Linden Ponds using recharge pattern 1, lack of significant water-level response from artificial recharge in wells southwest of the unnamed fault and northwest of Barrier J indicate that recharging in Linden Ponds using recharge pattern 1 is not an effective method of raising water levels in the area that has the most production wells in the basin. Water levels near Warm Creek and the Santa Ana River were not affected by artificial recharge at Linden Ponds.

Results of the particle-tracking simulation for artificial recharge at Linden Ponds starting in 1982 and ending in 2027 indicate that the water recharged in 1982 remained in the narrow corridor between the unnamed fault and the San Jacinto Fault and moved southeastward from Linden Ponds a distance of about 5 mi. The imported water moved at an average velocity of 900 ft/yr. One flow line crossed the central part of the unnamed fault, indicating that in ensuing years, the imported water may reach one of the current (1996) main pumping areas.

Results of the particle-tracking simulation for discontinued recharge in the Rialto–Colton Basin under average hydrologic conditions for an extended period (1982–2027 in this case), indicate that natural recharge was sufficient to move some imported water recharged during 1982–94, a distance of about 4 mi. None of the flow lines crossed the unnamed fault. The average velocity of imported-water movement was 700 ft/yr.

The water-level response to recharge pattern 1 starting in 2000 and ending in 2027 at Cactus Basin indicates that wells northwest of Barrier J and northeast of the unnamed fault are sufficiently isolated by the faults to be affected. Water levels southeast of Barrier J and north of the Santa Ana River and Warm Creek rose as much as 50 ft higher than discontinued recharge levels. Water levels near the Santa Ana River and Warm Creek again were not affected, indicating that a longer period of recharge would be needed to raise water levels in this area.

Simulated flow paths of imported water recharged in Cactus Basin using recharge pattern 1 beginning in 2000 and ending in 2027 showed that water moved southeastward, with an average velocity of about 500 ft/yr. Two production wells captured some of the water.

Results of all the predictive simulations, which are based on the current conceptualization of the Rialto–Colton Basin ground-water system, indicate that artificial recharge at Cactus Basin may be more effective than recharge at Linden Ponds at raising water levels in a greater part of the basin and that the imported water can be captured by production wells using recharge pattern 1. One flow line generated by recharge in Linden Ponds in 1982 crossed the unnamed fault but did not reach a production well. Artificial recharge at Cactus Basin raises water levels more effectively southeast of the unnamed fault where production wells are located, and artificial recharge at Linden Ponds raises water levels more effectively northeast of the unnamed fault.

The model is able to duplicate hydraulic heads fairly accurately northwest of Barrier J, just southeast of Barrier J in the northwest part of the basin during

1982–96, and in the central part of the basin during 1945–82. Where the conceptualization of model layers is oversimplified, however, the accuracy of the model is less certain. As a predictive tool, the ground-water flow model can provide qualitative information about flow directions and water-level changes and can be used to test alternative conceptualizations of the ground-water flow system. Alternative artificial-recharge scenarios can be used to predict water-level trends and track water particles from the recharge source for various time periods. Different artificial-recharge locations can be tested throughout the basin. Other management issues, such as changes in pumping patterns and quantities, also can be tested. Both the ground-water-flow and particle-tracking models should be used for long-term trends over broad areas rather than focusing on site-specific simulations.

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APPENDIX A

APPENDIX A

Two ARC/INFO AML (Arc Macro Language) programs, LOAD_DATA.AML and MK_WELLPKG.AML, are used to create MODFLOW-readable well-package files of initial, transient, or predictive conditions for the Rialto–Colton ground-water flow model. These programs, described in this appendix, make well-package management easier and data more accessible than with existing methods.

The programs have been tested with ARC/INFO software version 7.2.1 (a geographic information system from Environmental Systems Research Institute, Inc., Redlands, California) on a SUN workstation with a Sun 5.7 operating system. ARC/INFO stores information about geographic features in an INFO data base. INFO is a tabular data base used by ARC/INFO to store and manipulate feature-attribute tables and other related tables. For example, INFO allows INFO tables to be linked to one another to perform logical and arithmetic operations on rows and columns of data in the INFO tables.

The AML programs currently perform the following functions:

1. LOAD_DATA.AML uses INFO to load ("import" command) ASCII flat files into INFO tables of pumpage, hydraulic conductivity, recharge, underflow, aquifer top and bottom altitudes, aquifer source of well water, well construction, and model row/column locations of wells. It computes predictive annual totals for recharge, underflow, and pumpage, and saves results in INFO tables. Data in these INFO tables are accessed via INFO by MK_WELLPKG.AML and used to create the well-package file.
2. MK_WELLPKG.AML uses INFO to make the MODFLOW well-package file. It computes net pumpage from total pumpage. The user has the option to vary (through menu selections) the quantity of predictive data in order to test the scenarios of interest.

Both programs handle data for four or five model layers (the water-bearing unit and layer designations described in the "Model Grid" section) and thus meet the requirements of the Rialto–Colton study. An operational summary follows. For more detailed documentation, see the notes in the program code attached.

LOAD_DATA.AML

LOAD_DATA.AML imports ASCII flat files into INFO tables and computes and saves predictive data. Settings may be entered into a menu (data.menu), which is displayed once the program is invoked. Each category of data is entered into its own INFO table. In the menu (fig. A1), the user may select the data set to import, the number of model layers the data describe (4 or 5), the reported period of record contained in the flat file, the location of the flat file, and the settings used to compute the predictive data. The user may “APPLY” the settings to continue or “DISMISS” to close the program and not update the information.

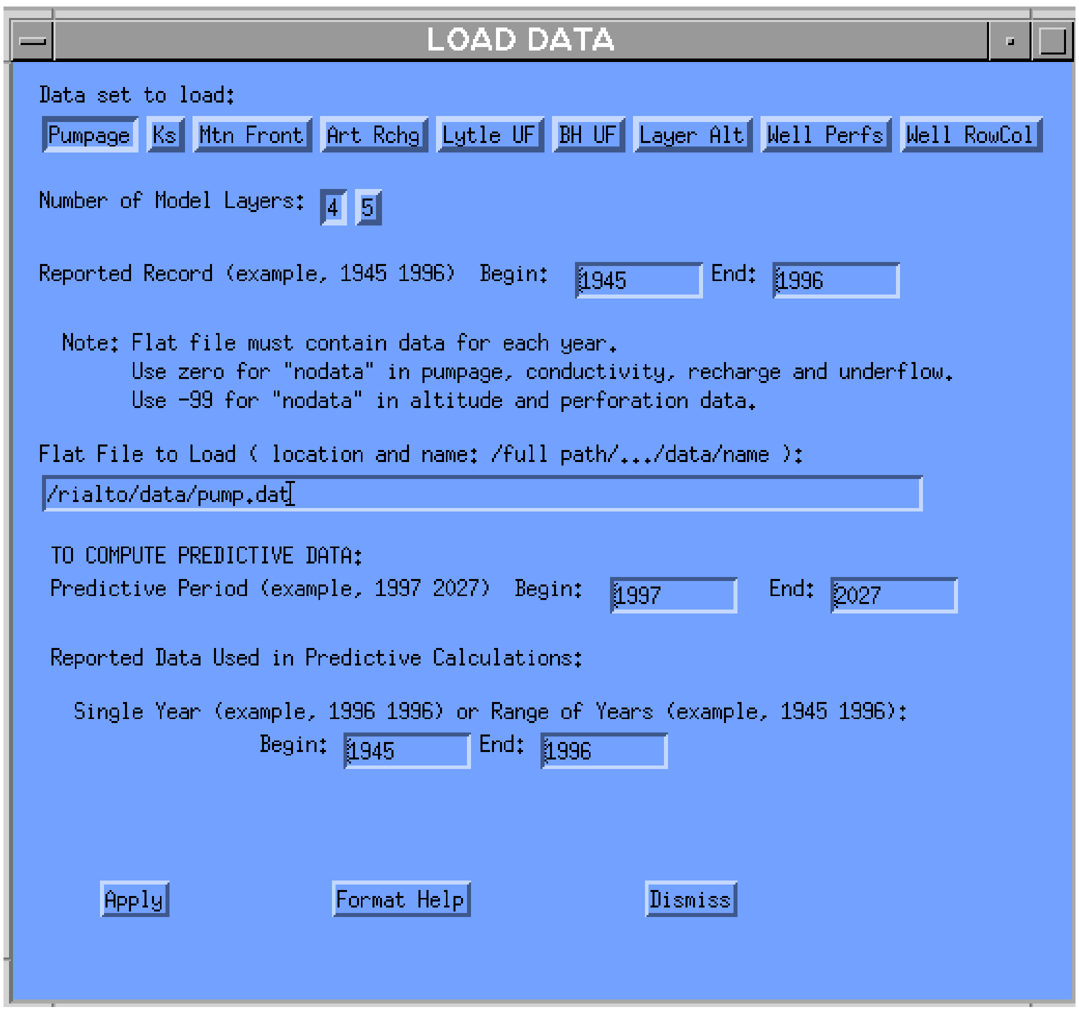

Figure A1. Menu (data.menu) displayed after LOAD_DATA.AML is run.

The flat file must be formatted to be accepted by INFO. Examples of these formats are available at the menu “FORMAT HELP” button (fig. A1), which displays a window when selected (load_examples.popup). The correct format is comma-delimited, with no carriage-return symbols or extraneous commas. For characters (names), single quotes should be placed around data when a space is included.

When data are imported into an INFO table, the old table of the same name is deleted and a new one is created. Therefore, it is necessary to import the entire data set, not just selected records, even if the operator is just updating records.

LOAD_DATA.AML enters each line of data into INFO as a single record, and each column of the flat file is entered as an “item” (a column) of the INFO table. INFO-table items holding pumpage or recharge data are labeled with a “Y” and the year of the measurement (for example, “Y1945”).

Predictive data are computed for a range of years (set in the menu), and from an average of reported data (single year or range of years) specified in the menu (fig. A1),

where: avg = summation of data selected / number of years of data selected

example: for predictive year Y2020, if averaging from a range of years,
Y2020 = Y1996 - Y1945 / 52

or if using a single year,
Y2020 = Y1996 / 1.

The INFO-table items storing predictive data are calculated to equal this average.

The INFO tables created for each data set are :

Button	Description of data set	INFO table
Pumpage	Total annual pumpage for 47 wells (acre-ft)	total_pumpage
Ks	Hydraulic conductivity of model layers (cells with wells) (ft/s)	well_ks4 or well_ks5
Mtn Front	Mountain-front-recharge, annual totals (ft^3/s)	rchg_mtn_ann
Art Rchg	Artificial recharge, annual totals (ft^3/s)	art_rchg_ann
Lytle UF	Underflow from Lytle basin, annual totals (ft^3/s)	uf_lytle_ann
BH UF	Underflow from Bunker Hill basin, annual totals (ft^3/s)	
uf_bh_ann		
Layer Alt	Model-layer altitudes of cells containing wells (ft)	layer_alt4 or layer_alt5
*Well Perfs	Altitudes of perforated intervals (ft)	well_perfs4 or well_perfs5
Well RowCol	Model grid row and column designations for the 47 wells	well_rowcol

*May contain layer designations and percent of total pumpage assigned to a layer, as determined by the user. These settings remain unchanged during the operation of MK_WELLPKG. AML.

The INFO table name includes “4” or “5” when data are specific to a model with that many layers (for example, “well_perfs4”) .

If desired, the model-layer designation and percentage of total pumpage assigned to the layer may be entered into INFO and will remain unchanged during the operation of MK_WELLPKG.AML. This is done when construction information is missing, or when the hydrologist has better knowledge of the contributing model layer (see "Pumpage" section of the report for a discussion of the logic employed to set these designations). Selecting the "Well Perfs" button imports the information into an INFO table it creates. The format (displayed for "Well Perfs" at the "FORMAT HELP" button) is:

```
PLEASE FORMAT FLAT FILES AS DESCRIBED BELOW:

   DATA CATEGORY                                                       BUTTON
----------------------------------------------------------------------------
---Well Perforations    (feet)                                    well_perfs
** To control the amount of pumpage assigned to a layer,
**   Set model-layer designations (and percent contributions if water
**   comes from more than one layer) in items 'layer' and 'pcnt(n)'
**   where: (pcnt(n) = maximum 5 decimal places)
** example:  enter layer one = 1, layer two and three = 23, etc.
****    pcnt(n) need only be set if more than one layer contributing  ****

INFO table:  WELL_PERFS_4
   items: wellid lse top_ele bop_ele layer pcnt1 pcnt2 pcnt3 pcnt4
   format (nodata = -99):
                      001N005W07P002E,2156.00,-99.00,-99.00,23,0,0.25,0.75,0
```

In the example above, 25 percent of total pumpage is assigned to layer 2 and 75 percent is assigned to layer 3. For more detailed documentation of LOAD_DATA.AML, see the program and menus attached.

MK_WELLPKG.AML

MK_WELLPKG.AML creates the MODFLOW-readable well-package file desired by the user. Options may be entered into a menu (wellpkg.menu), which is displayed once MK_WELLPKG.AML is run (fig. A2). The user may set the simulation type (initial, transient, or predictive conditions), simulation period, number of model layers, percentage of total pumpage not returned to the system as "irrigation return flow," and the percentage of total pumpage used in predictive computations. The user may "APPLY" the settings to continue or "DISMISS" to close the program and not update the information.

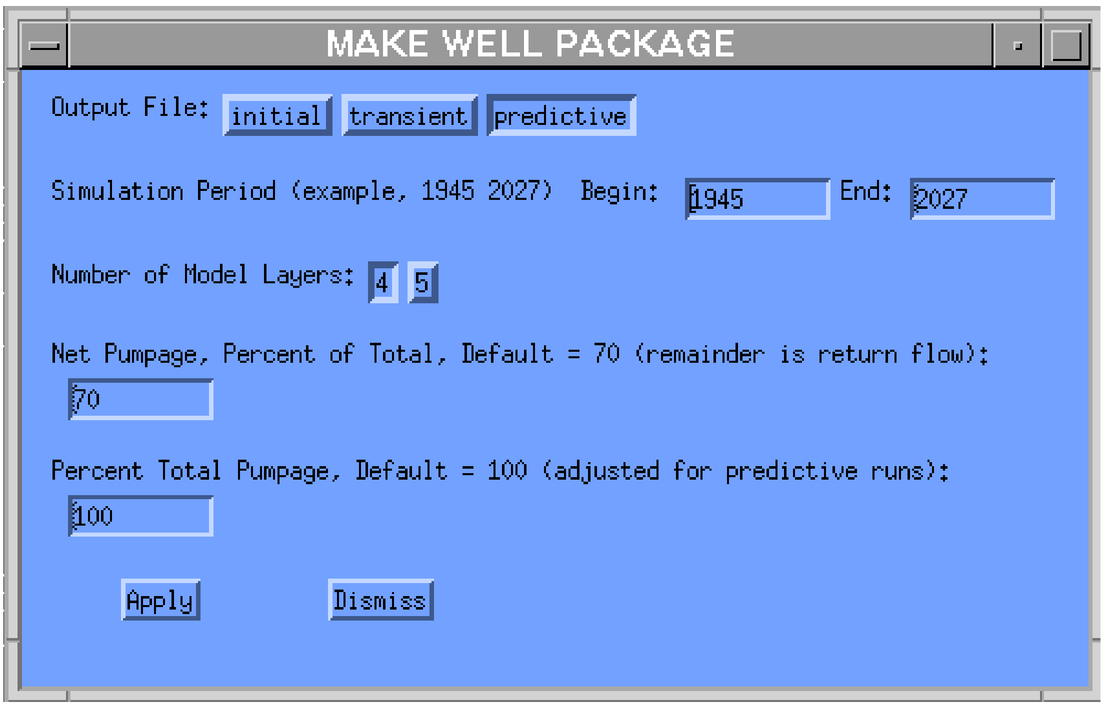

Figure A2. Menu displayed by MK_WELLPKG.AML.

This program uses four primary AML routines. The order of operation is: (1) the calc_perfs routine, which computes the length of the perforated interval within a model layer, (2) the calc_pcnt routine, which computes the weighted percentage of total pumpage contributed by a layer (if not specified in the well_perfs INFO table) from the lengths of perforated intervals (from calc_perfs routine) and the hydraulic conductivity of the layer at a given well, (3) the calc_qn routine, which distributes total pumpage vertically to model layers (in -ft^3/s) using the percentages computed in calc_pcnt for both the reported and predictive period, and adjusts predictive pumpage according to menu settings (results are stored in an INFO table), and (4) the pump_out routine, which reads the total pumpage assigned to model layers (from calc_qn routine) and computes net pumpage (based on the menu setting, fig. A2), and, reading from the computations of net pumpage and INFO tables of underflow, mountain-front recharge, and artificial recharge, creates the MODFLOW well-package file.

The INFO table holding the total pumpage assigned to model layers (created with calc_qn routine) is labeled to identify the file contents. For example, the name “QT_4_PRED80” indicates that total pumpage is assigned to a four-layer model and, for the predictive period (1997-2027), 80 percent of the pumpage estimated by LOAD_DATA.AML has been saved for output. Thus, well “A” (assuming a four- layer model and that all four layers are contributing), will show four records for each stress period -- one for each of the four model layers.

MK_WELLPKG.AML reads the INFO table of total pumpage assigned to model layers (for example, “QT_4_PRED80”) and computes net pumpage on the basis of the menu setting (fig. A2). For the Rialto–Colton model, net pumpage is 70 percent, (the remainder is assumed to be “irrigation-return flow,” see the “Irrigation-Return Flow” section of this report for a complete discussion). These values are unloaded directly into the MODFLOW well-package file.

For the period of record specified in the menu (fig. A2), MK_WELLPKG.AML outputs net pumpage and recharge in order of ascending stress period and model-layer number. The resulting MODFLOW well-package file contains the header information required by MODFLOW, and in a fix-formatted single record: layer, row, column, measurement in cubic feet per second (- for net pumpage or + for recharge data), and a source comment. An example of the MK_WELLPKG.AML output follows:

```
   287       40
89                                     Y1945
         1        60        70 -0.001034_Y1945          001S004W21N001E 01S04W21N01
         1        63        74 -0.060306_Y1945          001S004W28A006E 01S04W28A05
         1        64        74 -0.249211_Y1945          001S004W28G001E 01S04W28G01
         1        66        72 -0.446225_Y1945          001S004W28K001S 01S04W28K01
         1        55        72  1.344719_uf_bh_ann        550072
         1        56        73  1.344719_uf_bh_ann        560073
         1        57        73  1.344719_uf_bh_ann        570073
         1        61        76  1.344719_uf_bh_ann        610076
         1        62        77  1.344719_uf_bh_ann        620077
         1        63        77  1.344719_uf_bh_ann        630077
         2        50        59 -0.028987_Y1945          001S004W18B001E 01S04W18B01
         2        52        62 -0.065981_Y1945          001S004W17M001S 01S04W17M01
         2        60        70 -0.000391_Y1945          001S004W21N001E 01S04W21N01
         2        64        74 -0.005086_Y1945          001S004W28G001E 01S04W28G01
         2        66        72 -0.157958_Y1945          001S004W28K001S 01S04W28K01
```

The well-package file (example above) is named with the menu settings selected by the user. For example, the file “initial_4_n70.dat” holds initial-condition data for a four-layer model, wherein net pumpage is 70 percent of the total pumpage for a well. The file “predictive_5_p120_n70.dat” holds predictive simulation data for a five-layer model, wherein the predictive data are 120 percent of values computed by LOAD_DATA.AML, and the net pumpage (for the entire simulation period) is 70 percent of the total pumpage for the well. See the program and menus attached for specific documentation of MK_WELLPKG.AML.

Coding for DATA.MENU:

```
/*------------------------------------------------------------------------
7 data.menu
/* field definitions
 Data set to load:
 %class1

 Number of Model Layers: %class2

 Reported Record (example, 1945 1996)  Begin: %b_year  End: %e_year

   Note: Flat file must contain data for each year.
         Use zero for "nodata" in pumpage, conductivity, recharge, and underflow.
         Use -99 for "nodata" in altitude and perforation data.

 Flat File to Load ( location and name: /full path/.../data/name ):
 %class3

  TO COMPUTE PREDICTIVE DATA:
  Predictive Period (example, 1997 2027)  Begin: %b_year_p  End: %e_year_p

  Reported Data Used in Predictive Calculations:

    Single Year (example, 1996 1996) or Range of Years (example, 1945 1996):
                    Begin: %b_year_av End: %e_year_av




     %apply              %format_help              %dismiss

%class1 CHOICE .info_t PAIRS   INITIAL 'total_pumpage' ~
      'Pumpage' 'total_pumpage' 'Ks' 'well_ks' ~
      'Mtn Front' 'rchg_mtn_ann' 'Art Rchg' 'art_rchg_ann' ~
      'Lytle UF' 'uf_lytle_ann' 'BH UF' 'uf_bh_ann' 'Layer Alt' 'layer_alt' ~
      'Well Perfs' 'well_perfs' 'Well RowCol' 'well_rowcol'
%class2 CHOICE .no_l SINGLE   INITIAL '4'  '4' '5'
%b_year INPUT .b_year 10 TYPEIN YES INITIAL 1945 SCROLL NO REQUIRED REAL
%e_year INPUT .e_year 10 TYPEIN YES INITIAL 1996 SCROLL NO REQUIRED REAL
%class3 INPUT .flat_f 75 TYPEIN YES REQUIRED CHARACTER
%b_year_p INPUT .b_year_p 10 TYPEIN YES INITIAL 1997 SCROLL NO REQUIRED REAL
%e_year_p INPUT .e_year_p 10 TYPEIN YES INITIAL 2027 SCROLL NO REQUIRED REAL
%b_year_av INPUT .b_year_av 10 TYPEIN YES INITIAL 1945 SCROLL NO REQUIRED REAL
%e_year_av INPUT .e_year_av 10 TYPEIN YES INITIAL 1996 SCROLL NO REQUIRED REAL

%apply BUTTON 'Apply' &return
%format_help BUTTON 'Format Help' &popup load_examples.popup
%dismiss BUTTON CANCEL 'Dismiss' &s .exit_pgm = .true. ; &dv .info_t ~
         .no_l .b_year .e_year .flat_f .b_year_p .e_year_p .b_year_av ~
         .e_year_av ; &return
%FORMOPT SETVARIABLES RETURN
%FORMINIT &s .exit_pgm = .false.
```

Coding for LOAD_EXAMPLES.POPUP

```
PLEASE FORMAT FLAT FILES AS DESCRIBED BELOW:

   DATA CATEGORY                                                        BUTTON
----------------------------------------------------------------------------
---Total Pumpage    (acre-feet)                                        Pumpage
INFO table: total_pumpage
     items: wellid otherid1 otherid2 y1945...y1996
     format (nodata = 0):  001S005W12A001E,name1,name2,0,27,..,100

---Hydrologic Conductivity     (ft3/s)                                      Ks
INFO table:  WELL_KS_4
     items: wellid k1 k2 k3 k4
     format (nodata = 0):  001S005W12A001E,0,0,0.0005787,0.0001447

INFO table:  WELL_KS_5
     items: wellid k1 k2 k3 k4 k5
     format (nodata = 0):  001S005W12A001E,0,0,0,0.0005787,0.0001447


---Mountain Front Rchg  (ft3/s)                                      Mtn_Front
INFO table:  RCHG_MTN_ANN
     items: layer row column Y1945....Y2027
     format (nodata = 0):  1,1,1,0.237765,0.247835,....,0.247835


---Lytle Underflow  (ft3/s)                                           Lytle_UF
INFO table:  UF_LYTLE_ANN
     items: layer row column Y1945....Y2027
     format (nodata = 0):  1,1,1,0.237765,0.247835,....,0.247835


---Bunker Hill Underflow  (ft3/s)                                        BH_UF
INFO table:   UF_BH_ANN
     items: layer row column Y1945....Y2027
     format (nodata = 0):  1,1,1,0.237765,0.247835,....,0.247835


---Model Layer Altitudes  (feet)                                     layer_alt
INFO table:  LAYER_ALT_4
   items: wellid top1 bot1 top2 bot2 top3 bot3 top4 bot4
   format (nodata = -99):  001N005W07P002E,-99,-99,1850,1720,-99,-99,-99,-99

INFO table:  LAYER_ALT_5
   items: wellid top1 bot1 top2 bot2 top3 bot3 top4 bot4 top5 bot5
   format (nodata = -99):
                   001N005W07P002E,-99,-99,-99,-99,1850,1720,-99,-99,-99,-99

---Model row/column of well locations                                 well_rowcol
INFO table:  WELL_ROWCOL
   items: wellid row col
   format (all data required):                          001S005W12A001E,43,55
```

```
---Well Perforations    (feet)                                    well_perfs
** To control the amount of pumpage assigned to a layer,
**   Set model-layer designations (and percent contributions if water
**   comes from more than one layer) in items 'layer' and 'pcnt(n)'
**   where: (pcnt(n) = maximum 5 decimal places)
** example:  enter layer one = 1, layer two and three = 23, etc.
****    pcnt(n) need only be set if more than one layer contributing  ****

INFO table:  WELL_PERFS_4
   items: wellid lse top_ele bop_ele layer pcnt1 pcnt2 pcnt3 pcnt4
   format (nodata = -99):
                      001N005W07P002E,2156.00,-99.00,-99.00,23,0,0.25,0.75,0

INFO table:  WELL_PERFS_5
   items: wellid lse top_ele bop_ele layer pcnt1 pcnt2 pcnt3 pcnt4 pcnt5
   format (nodata = -99):
                  001N005W07P002E,2156.00,-99.00,-99.00,34,0,0,0.25,0.25,0.5
```

Coding for LOAD_DATA.AML:

```
/*-----------------------------------------------------------------------------
/*
/*  Program: load_data.aml     Written for Linda Woolfenden by KMKoczot
/*  Version: 1.0
/*  Language: AML
/*  Arc Version and Platform: 7.2.1 UNIX
/*  Subsystem: Arc
/*
/*::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
/*
/* Purpose: To load Rialto-Colton GW Model data into INFO TABLES for
/* use in the program mk_wellpkg.aml.  The data that may be loaded include
/* total pumpage, conductivity, mountain-front recharge, artificial recharge,
/* underflow (Lytle and Bunker Hill areas), model-layer altitudes by
/* row/column, well-perforation altitudes, and model grid-cell location
/* for each well.
/*
/*::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
/*
/* Menu called: data.menu
/*
/* Popup window (called in data.menu at 'help' button): load_examples.popup
/*
/* Popup window and menu called by: load_data.aml
/*
/*::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
/*
/* Variables used by program (in order of operation):
/*     set in data.menu:
/*  Name:          Type:      Description:
/* .info_t     character     Data set to make into INFO Table.
/* .no_l       integer       Number of model layers in flat file data
/*                                (4 OR 5).
/* .b_year     real number   Beginning year of reported data in flat file.
/* .e_year     real number   Ending year of reported data in flat file.
/* .flat_f     character     Location/name of flat file to load.
/* .b_year_p   real number   Beginning year, predictive period (format yyyy).
/* .e_year_p   real number   Ending year, predictive period (format yyyy).
/* .b_year_av  real number   Beginning year, reported data to compute
/*                                predictive data from (format yyyy).
/* .e_year_av  real number   Ending year, reported data to compute
/*                                predictive data from (format yyyy).
/* .exit_pgm   character     Closes program if conditions are 'true'.
/*
/*    set in load_data.aml:
/* .exit_pgm   character     Closes program if conditions are 'true'.
/*  tempcov    character     Temporary coverage created and killed to add
/*                                the INFO subdirectory.
/* .f          character     Name of INFO table to be created.
/*  junk       character     Variable set to delete a file.
/* .n          integer       Model-layer number used in an item name.
/* .date       integer       Year of reported data.
/* .date_p     integer       Year of predictive data.
```

```
/*  Y          character     Name of item to hold predictive data.
/* .final      character     Name of INFO table successfully created.
/*
/*::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
/*
/* Routines used in program (alphabetical order):
/*     Name:              Description:
/* art_rchg_ann_rtne   Calls routine 'recharge_rtne' and sets INFO table
/*                          name to 'art_rchg_ann'.
/* bailout_rtne        Closes program if problem is encountered.
/* check_settings      Verifies required INFO tables exist, user has
/*                          permission to work in the directory, and the
/*                          directory is an ARC/INFO workspace.
/* cleanup_rtne        Closes the variables set by this program.
/* layer_alt_rtne      Creates the INFO table for model-layer top and
/*                          bottom altitudes (with data set for
/*                          4 or 5 model layers).
/* predict_years       Computes predictive data and stores results
/*                          in INFO table items.
/* rchg_mtn_ann_rtne   Calls routine 'recharge_rtne' and sets INFO table
/*                          name to 'rchg_mtn_ann'.
/* recharge_rtne       Creates the INFO table for a recharge data set.
/* total_pumpage_rtne  Creates the INFO table for total_pumpage.
/* uf_lytle_ann_rtne   Calls routine 'recharge_rtne' and sets INFO table
/*                          name to 'uf_lytle_ann'.
/* uf_bh_ann_rtne      Calls routine 'recharge_rtne' and sets INFO table
/*                          name to 'uf_bh_ann'.
/* well_ks_rtne        Creates the INFO table for conductivity
/*                          (with data set for 4 or 5 model layers).
/* well_perfs_rtne     Creates the INFO table for well construction
/*                          altitudes (land surface, top and bottom
/*                          of perforations) and percent of total pumpage
/*                          and model-layer number contributing water.
/*                          (with data set for 4 or 5 model layers).
/* well_rowcol_rtne    Creates the INFO table holding model-layer
/*                          row column of well locations.
/*
/*::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
/*
/* History:
/* Author/Site,     Date,     Version    Event
/* -------------------------------------------------------------------------
/* kmkoczot         8/20/98    ---       load_data.aml first cut written
/*                                                uses data.menu.
/* kmkoczot        12/10/98    ---       load_data.aml revised to add
/*                                                altitudes.
/* kmkoczot          3/3/99    ---       load_data.aml revised to send
/*                                                 warning to screen if
/*                                                 working file is missing.
/* kmkoczot         3/12/99    ---       load_examples.popup written
/* kmkoczot            8/99    1.0       load_data.aml revised to use new
/*                                                 data.menu, which includes
/*                                                 option to load pumpage.
/*                                                 Modified some routines
/*                                                to reduce processing time.
```

```
/*                                                  Added total_pumpage_rtne
/*                                                  to create pumpage INFO
/*                                                  table.  Added
/*                                                  variable and routine
/*                                                  descriptions to header.
/*                                                  Added comment lines to
/*                                                  coding.  (Final coding)
/*
/*---------------------------------------------------------------------------
/*
/* Disclaimer:
/*   Although this program has been used by the U.S. Geological Survey, no
/* warranty, expressed or implied, is made by the USGS as to the accuracy
/* and functioning of the program and related program material nor shall the
/* fact of distribution constitute any such warranty, and no responsibility
/* is assumed by the USGS in connection herewith.
/*
/*---------------------------------------------------------------------------

&severity &error &routine bailout_rtne

&terminal 9999
&menu data.menu &form &STRIPE 'LOAD DATA'
  &if %.exit_pgm%  &then &return Exiting Program Load_data.aml

  &messages &off
/* Check to see if flat file (%.flat_f%) exists.
   &call check_settings

/* Create INFO table.
   &call %.info_t%_rtne

/* List finished INFO table below.
   &type [quote FINISHED   :>   .  NEW INFO TABLE CREATED.    SEE BELOW: ]
   &type [quote ]
&messages &on
 dir info %.final%

&messages &off
/* Cleanup the directory.
   &call cleanup_rtne

&messages &on

&return  /* closes load_data.aml


/*----------------------ROUTINES------------------------------------------

/*---------------------bailout_rtne
&routine bailout_rtne
 &severity &error &ignore
  &if [quote [translate [show program]]] = 'TABLES' &then QUIT
```

```
   &s .exit_pgm = .true.
    &messages &on
    &type 'An error has occurred in load_data.aml.'
     &if %.exit_pgm%  &then &return Exiting Program load_data.aml
    &call cleanup_rtne
&return  /* closes bailout_rtne


/*---------------------check_settings
&routine check_settings
/* verify the user has write permission to the current workspace
 &if not [access [show workspace] -write] &then
    &do
      &type;&type Warning!! User [upcase [username]] does not have write ~
            permissions
      &type to the current workspace. The program has been canceled.
      &return
    &end  /* if-then-do

/* verify the current directory is an arc/info workspace
 &if not [exists [show workspace] -workspace] &then
    &do
      &s tempcov = [scratchname -dir]
      create %tempcov%
      kill %tempcov% all  /* this creates the needed INFO subdirectory.
    &end  /* if-then-do

/* Check to see flat file specified in data.menu exists.
 &if ^ [exists %.flat_f%] &then
   &do
     &type [quote Flat file not found in: %.flat_f% ]
     &type [quote Please check path and file name.]
          &s .exit_pgm = .true.
     &messages &on
      &if %.exit_pgm%  &then &return Exiting Program load_data.aml
   &end  /* if-then-do
&return

/*---------------------total_pumpage_rtne
&routine total_pumpage_rtne    /* Loads total_pumpage (AF) .

/*--define name of INFO table to hold data.
 &s .f = %.info_t%
 &if [exists %.f% -info] &then &s junk [delete %.f% -info]
 &type [quote LOADING %.flat_f% (%.b_year%-%.e_year%)]
 &type [quote .                  TO INFO TABLE: %.f%]

/*--define INFO table
TABLES
  define %.f%
    WELLID 15    15     C
    OTHERID1 15 15 C
    OTHERID2 15 15 C
    ~
```

```
    sel
  /* additems to hold reported total pumpage (acre-feet) of each well
    &do .date = %.b_year% &to %.e_year% &by 1
      additem total_pumpage Y%.date% 6     6     I
    &end  /* do


/*--load data from flat file.
  sel %.f%
  add from %.flat_f%
  commit
QUIT /*TABLES

/*--compute and add predictive data
  /* additems to hold predictive data.
        &do .date_p = %.b_year_p% &to %.e_year_p% &by 1
           additem %.f% %.f% Y%.date_p% 6 6 I
        &end  /* do
        additem %.f% %.f% avg 10 10 n 2
        additem %.f% %.f% tot_range 15 15 n 2


  /* compute predictive data and load value to items added above.
     &call predict_years

 &s .final = %.f%
&return  /* closes total_pumpage_rtne


/*---------------------well_ks_rtne
&routine well_ks_rtne    /* Load conductivities.

/*--define name of INFO table to hold data.
 &s .f = %.info_t%_%.no_l%
 &if [exists %.f% -info] &then &s junk [delete %.f% -info]
 &type [quote LOADING %.flat_f% (%.b_year%-%.e_year%)]
 &type [quote .                    TO INFO TABLE: %.f%]

/*--define INFO table
TABLES
  define %.f%
    WELLID 15    15     C
    ~
    sel
  /* additems to hold conductivity (ft/sec) of each layer
      &do .n = 1 &to %.no_l% &by 1
         additem %.f% k%.n% 11    11     N      7
      &end  /* do

/*--load data from flat file.
  sel %.f%
  add from %.flat_f%
  commit
QUIT /*TABLES
```

```
 &s .final = %.f%
&return  /* closes well_ks_rtne


/***---------------------NOTE:   recharge_rtne     is used to load:
/***   rchg_mtn_ann     uf_lytle_ann      uf_bh_ann

     /*---------------------for art_rchg_ann
     &routine art_rchg_ann_rtne
       &call recharge_rtne     /* loads recharge data (ft3/s).
     &return  /* closes rchg_mtn_ann_rtne

     /*---------------------for rchg_mtn_ann
     &routine rchg_mtn_ann_rtne
       &call recharge_rtne
     &return  /* closes rchg_mtn_ann_rtne

     /*---------------------for uf_lytle_ann
     &routine uf_lytle_ann_rtne
       &call recharge_rtne
     &return  /* closes uf_lytle_ann_rtne

     /*---------------------for uf_bh_ann
     &routine uf_bh_ann_rtne
       &call recharge_rtne
     &return  /* closes uf_bh_ann_rtne


/*---------------------recharge_rtne
&routine  recharge_rtne /* Load recharge and underflow (ft3/s).

/*--define name of INFO table to hold data.
 &s .f = %.info_t%
 &if [exists %.f% -info] &then &s junk [delete %.f% -info]
 &type [quote LOADING %.flat_f% (%.b_year%-%.e_year%)]
 &type [quote .                   TO INFO TABLE: %.f%]

/*--define INFO table
TABLES
  define %.f%
    LAYER  4    10     I
    ROW    4    10     I
    COL    4    10     I
  ~
  /* Set years to load to INFO table.
        &do .date = %.b_year% &to %.e_year% &by 1
        /* additems to hold mountain-front recharge (ft3/s).
              additem %.f% Y%.date% 10    10     N      6
        &end  /* do

/*--load data from flat file.
  sel %.f%
  add from %.flat_f%
```

```
  commit

/*--Create the common item, 'CELL'.
  redefine
    5
    cell 8 8 i
  ~
  sel
QUIT /*TABLES

/*--compute and add predictive data
  /* additems to hold predictive data.
        &do .date_p = %.b_year_p% &to %.e_year_p% &by 1
           additem %.f% %.f% Y%.date_p% 10 10 N 6
        &end  /* do
        additem %.f% %.f% avg 10 10 n 6
        additem %.f% %.f% tot_range 15 15 n 6

  /* compute predictive data and load value to items added above.
     &call predict_years

 &s .final = %.f%
&return /* closes recharge_rtne


/*---------------------layer_alt_rtne
&routine layer_alt_rtne
/*  Loads top and bottom altitude for model with layers specified in menu.

/*--define name of INFO table to hold data.
 &s .f = %.info_t%_%.no_l%
 &if [exists %.f% -info] &then &s junk [delete %.f% -info]
 &type [quote LOADING %.flat_f% (%.b_year%-%.e_year%)]
 &type [quote .                   TO INFO TABLE: %.f%]

/*-- define the new INFO table
TABLES
  define %.f%
    WELLID 15 15 C
    ~
    sel

  /* additems to hold top and bottom model layer altitudes
  /*   for cells containing wells.
  /*      example:  item top1 = top of layer 1 altitude (feet)
      &do .n = 1 &to %.no_l% &by 1
         additem %.f% top%.n%  8 8 N 1
         additem %.f% bot%.n%  8 8 N 1
      &end  /* do

/*--load data from flat file.
  sel %.f%
  add from %.flat_f%
  commit
```

```
QUIT  /* TABLES

 &s .final = %.f%
&return  /* closes layer_alt_rtne


/*---------------------well_perfs_rtne
&routine well_perfs_rtne   /* Loads new perforation altitude data.
/*  Note: This data set includes items LAYER and PCNT%no_l%,
/*        These may have been set by the hydrologist in the flat file.
/*        Otherwise, they are computed by MK_WELLPKG.AML.
/*--define name of INFO table to hold data.
 &s .f =  %.info_t%_%.no_l%
 &if [exists %.f% -info] &then &s junk [delete %.f% -info]
 &type [quote LOADING %.flat_f% (%.b_year%-%.e_year%)]
 &type [quote .                   TO INFO TABLE: %.f%]

/*-- define the new INFO table
TABLES
  define %.f%
    WELLID               15    15     C
    LSE                   8     8     N      2
    TOP_ELE               8     8     N      2
    BOP_ELE               8     8     N      2
    LAYER                 5    10     I
    ~
    sel

  /* additems to hold percent of total pumpage in layer n.
  /*      example:   item PCNT1 = percent of total from layer 1.
      &do .n = 1 &to %.no_l% &by 1
         additem %.f% PCNT%.n%  7     7     N      5
      &end  /* do
  ~

/*--load data from flat file.
  sel %.f%
  add from %.flat_f%
  commit
QUIT /* TABLES
 &s .final = %.f%
&return  /* closes well_perfs_rtne


/*---------------------well_rowcol_rtne
&routine well_rowcol_rtne /* Loads row/column modelgrid cell for each well.

/*--define name of INFO table to hold data.
 &s .f = %.info_t%
 &if [exists %.f% -info] &then &s junk [delete %.f% -info]
 &type [quote LOADING %.flat_f% (%.b_year%-%.e_year%)]
 &type [quote .                   TO INFO TABLE: %.f%]
```

```
/*-- define the new INFO table
TABLES
   define %.f%
    WELLID                15    15     C
     ROW                   4     4     I
     COL                   4     4     I
   ~

/*--load data from flat file.
   sel %.f%
   add from %.flat_f%
   commit

/*--Create the common item, 'CELL'.
   redefine
   16
   cell 8 8 i
   ~
QUIT  /* TABLES
 &s .final = %.f%
&return  /* closes well_rowcol_rtne


/*---------------------predict_years
&routine predict_years
/* calcs predictive years to the average of reported years
/* where: avg = average value of years selected in menu
/*        avg = summation of data selected/ number of years
/*
/*  example: for predictive year Y2020, if
/*              a range of years Y2020 = Y1996 - Y1945 / 52
/*     or     if a single year   Y2020 = Y1996 / 1

TABLES
   sel %.f%
   /* compute average value from range of years specified in the menu.
   calc tot_range = 0   /* just in case it holds some other value.
   commit
&type [quote COMPUTING PREDICTIVE DATA FROM AVERAGE OF YEARS ~
       %.b_year_av%-%.e_year_av%]
   &do .date = %.b_year_av% &to %.e_year_av% &by 1
        calc tot_range = tot_range + Y%.date%
        commit
   &end  /* do
   &s denom = %.e_year_av% - %.b_year_av% + 1
   calc avg = tot_range / %denom%
   commit

   /* calculate predicted years to equal the average value.
   &do .date = %.b_year_p% &to %.e_year_p% &by 1
      &s Y = Y%.date%
        calc %Y% = avg  /* average computed above.
        commit
   &end  /* do
```

```
QUIT  /* TABLES
&return


/*----------------------cleanup_rtne
&routine cleanup_rtne  /* closes global variables set by this program.
  &dv .info_t .no_l .b_year .e_year .flat_f .b_year_p .e_year_p ~
     .b_year_av .e_year_av .exit_pgm .f .n .date .date_p .final
&return

/*----------------------end of routines.
```

Coding for WELLPKG.MENU

```
7 wellpkg.menu
/* field definitions
 Output File:%class1

 Simulation Period (example, 1945 2027)  Begin: %b_year   End: %e_year

 Number of Model Layers:%class2

 Net Pumpage, Percent of Total, Default = 70 (remainder is return flow):
  %class3

 Percent Total Pumpage, Default = 100 (adjusted for predictive runs):
  %class4

      %apply         %dismiss

%class1 CHOICE .QTYPE SINGLE INITIAL ‘initial’ ~
                ‘initial’ ‘transient’ ‘predictive’
%b_year INPUT .b_year 10 TYPEIN YES INITIAL 1945 SCROLL NO REQUIRED REAL
%e_year INPUT .e_year 10 TYPEIN YES SCROLL NO REQUIRED REAL
%class2 CHOICE .no_l SINGLE  INITIAL ‘4’   ‘4’ ‘5’
%class3 INPUT .pcnt_ir 10 TYPEIN YES INITIAL 70 SCROLL NO REQUIRED ~
                        RANGE 0 100 INTEGER
%class4 INPUT .pcnt_qt 10 TYPEIN YES INITIAL 100 SCROLL NO REQUIRED ~
                        RANGE 0 10000 INTEGER
%apply BUTTON ‘Apply’ &return
%dismiss BUTTON CANCEL ‘Dismiss’ &s .exit_pgm = .true. ; &dv .QTYPE ~
        .b_year .e_year .no_l .pcnt_ir .pcnt_qt ; &return
%FORMOPT SETVARIABLES RETURN
%FORMINIT &s .exit_pgm = .false.
```

Coding for MK_WELLPKG.AML

```
/*---------------------------------------------------------------------------
/*
/*  Program: mk_wellpkg.aml   Written for Linda Woolfenden by KMKoczot.
/*  Version: 1.0
/*  Language: AML
/*  Arc Version and Platform: 7.2.1 UNIX
/*  Subsystem: Arc
/*
/*:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
/*
/* Purpose: Creates a MODFLOW-readable well-package file for initial,
/* transient, or predictive conditions, to be used in the Rialto-Colton
/* MODFLOW model.  Computes net pumpage from total pumpage.  Vertically
/* distributes net pumpage to model layers according to the location of
/* perforated intervals and the conductivity of the model layer.  Pumpage
/* quantities can be specified for a model layer (in the well_perfs file
/* loaded by LOAD_DATA.AML), overriding this feature.  Pumpage values for
/* predictive scenarios (1997-2027) may be adjusted by any percentage to
/* evaluate the effects of future increases and (or) decreases in pumpage.
/* The percentage of total pumpage used in the predictive computations,
/* the irrigation efficiency rate used in the net pumpage computations, the
/* type of output (initial, transient or predictive), the number of model
/* layers, and the simulation period, are set in the menu.  Output includes
/*  -Q (net pumpage) and +Q (mountain-front and artificial recharge, and
/* underflow).
/*
/*:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
/*
/* Menu called: wellpkg.menu
/*
/* Menu called by: mk_wellpkg.aml
/*
/*:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
/*
/* UNIX SYSTEM tools used in program:
/*    vi editor          used in "calc_perfs" routine.
/*    paste command      used in "calc_perfs" routine.
/*
/*:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
/*
/* Variables used by program (in order of operation):
/*     set in wellpkg.menu:
/*  Name:          Type:      Description:
/* .QTYPE    character     Type of MODFLOW output file (initial,
/*                              (transient or predictive conditions).
/* .b_year   real number   Beginning year of simulation period (format yyyy).
/* .e_year   real number   Ending year of simulation period (format yyyy).
/* .no_l     integer       Number of model layers to output to MODFLOW
/*                              file (four or five).
/* .pcnt_ir  integer       Net pumpage (percent of total pumpage).  The
/*                              remainder is assumed to be return flow.
/* .pcnt_qt  integer       Percent of total pumpage used in predictive
/*                              computations.
```

```
/* .exit_pgm   character   Closes program if conditions are 'true'.
/*
/*     set in mk_wellpkg.aml:
/* .exit_pgm     character   Closes program if conditions are 'true'.
/* tempcov       character   Temporary coverage created and killed to add
/*                                the INFO subdirectory.
/* i_f           character   Lists of INFO tables verified in
/*                               check_settings routine.
/* junk          character   Variable set to delete a file.
/* f             character   Lists of INFO tables and flat files to delete
/*                               in clean-up routines.
/* n             integer     Model-layer number used in an item name.
/* i             character   Lists of INFO-table items to drop from INFO
/*                               tables (in clean-up routines).
/* yr            integer     Year used in an item name (format yyyy).
/* unload_years  character   String of items holding net pumpage that are
/*                               unloaded to a temporary file.
/* .mfile        character   Name of MODFLOW file created by mk_wellpkg.aml.
/* X             character   Lists of INFO tables.
/* .IR           integer     Irrigation efficiency rate.
/* header        character   The first line unloaded to the MODFLOW file.
/*                               It contains '   287       40' .
/* .date         integer     Year of simulation period.
/* Y             character   Name of item (a stress period) holding
/*                               simulated data.
/* C1            integer     Count of net pumpage from records in stress
/*                               period %Y% that are in an active area and
/*                               layer of the MODFLOW model.
/* C%X%          integer     Count of records in stress period %Y% that
/*                               are in an active area and layer of the
/*                               MODFLOW model.  These records are counted
/*                               from the recharge INFO tables.
/* name          character   Name of an INFO-table holding recharge data.
/* C3            integer     Summation of the totals found in C1 and C%X%
/*                               for stress period %Y%.
/* headvar       character   The line unloaded to the MODFLOW file at the
/*                               beginning of each stress period.  It
/*                               contains a total of records in the stress
/*                               period %C3% (read by MODFLOW), and a
/*                               stress-period label %Y%.
/*
/*:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
/*
/* Routines used in program (in order of operation):
/*     Name:              Description:
/* bailout_rtne        Closes program if problem is encountered.
/* check_settings      Verifies required INFO tables exist, user has
/*                          permission to work in the directory, and the
/*                          directory is an ARC/INFO workspace.
/*
/* calc_perfs           Makes INFO table: layer_perfs%.no_l%.  See NOTES.
/*  mk_layer_perfs4      Called by "calc_perfs" routine.
/*                          Following seven assumptions for each well
/*                          (see notes in "calc_perfs" routine), sums the
```

```
/*                            length of the perforated interval per model
/*                            layer into a single record (four-layer model
/*                            only).
/*  mk_layer_perfs5       Called by "calc_perfs" routine.  Sums the
/*                            length of the perforated interval per model
/*                            layer into a single record
/*                            (like mk_layer_perfs4 but for a five-layer
/*                            model only).
/*  redefine_4_rtne       Called by "calc_perfs" routine.  Redefines a new
/*                            model-layer number.   Model-layer numbers are
/*                            assigned in the routine based on the location
/*                            of perforated intervals, unless layers were
/*                            already assigned in well_perfs_%.no_l%
/*                            (four-layer model only).
/*  redefine_5_rtne       Called by "calc_perfs" routine.  Redefines a new
/*                            model-layer number (like redefine_4_rtne but
/*                            for a five-layer model only).
/*  clean_layer_perfs4    Called by "calc_perfs" routine.  Deletes extra
/*                            items in layer_perfs%.no_l% (four-layer model
/*                            only).
/*  clean_layer_perfs5    Called by "calc_perfs" routine.  Deletes extra
/*                            items in layer_perfs%.no_l% (four-layer model
/*                            only).
/*
/* calc_pcnt            Makes INFO table: layer_pcnts%.no_l%.  See NOTES.
/*  calc_denom4          Called by "calc_pcnt" routine.  Computes the
/*                            denominator of the equation to find the
/*                            percentage of total pumpage coming from the
/*                            model layer perforated by a well.  This is
/*                            computed from the perforated length and the
/*                            conductivity of the model layer of that well
/*                            (four-layer model only).
/*  calc_denom5          Called by "calc_pcnt" routine. Computes the
/*                            denominator of an equation as in "calc_denom4"
/*                            (five-layer model only).
/*
/* calc_qn              Makes INFO table: QT_%.no_l%_pred%.pcnt_qt%.
/*                            See NOTES.
/*
/* pump_out             Makes MODFLOW well-package file.  See NOTES.
/*  cleanup_pump_out     Called by "pump_out" routine.  Deletes extra
/*                            items in QT_%.no_l%_pred%.pcnt_qt%
/*                            and the recharge INFO tables.
/*
/* cleanup_rtne         Closes the variables and routines set by this
/*                            program.
/*
/*::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
/*
/* NOTES:
/*     Mk_wellpkg.aml must be run in the directory containing the
/* INFO tables it will read from.
/*
/*     Mk_wellpkg.aml permits the user to create MODFLOW-readable
```

```
/* well-package files for the Rialto-Colton ground-water flow model. In the
/* menu, the user may select initial, transient, or predictive conditions,
/* set the simulation period, choose between four and five model layers,
/* specify net pumpage (as a percent of total pumpage) to output, and
/* specify the percentage of total pumpage to use for predictive data.
/*
/*
/*     Mk_wellpkg.aml was created by catenating four amls together.
/* The amls became primary routines in this program and are called
/* (in order of processing): calc_perfs, calc_pcnt, calc_qn, and pump_out.
/*
/*     "Calc_perfs" routine creates the INFO table layer_perfs%.no_l% from
/* INFO tables well_perfs_%.no_l% and layer_alt_%.no_l%.  These INFO
/* tables were created using load_data.aml.  Unless already set in
/* well_perfs_%.no_l%, this routine identifies the model layer(s) the
/* well is perforated in, and determines the length of perforated interval
/* within model layer(s) for each well.
/*
/*     where: n = model-layer number
/*            L(n) = length of perforated interval in layer n (ft)
/*
/*     "Calc_pcnt" routine creates the INFO table layer_pcnts%.no_l% from
/* layer_perfs%.no_l% (killed at end) and from well_ks_%.no_l%.  Unless
/* already set in well_perfs_%.no_l%, this routine calculates the
/* percentage of the total perforated interval in each model layer
/* (weighted by conductivity of the model layer).   It assigns model-layer
/* numbers where not already assigned in well_perfs_%.no_l%.
/*
/*     where: k(n) = hydraulic conductivity of layer n (ft/sec)
/*            pcnt(n) = L(n) * k(n) / L1*k1 + L2*k2 ... + L(n)*k(n)
/*            pcnt(n) = percentage of total pumpage from layer n
/*                                        ( a representative fraction)
/*
/*     "Calc_qn" routine creates the INFO table
/* QT_%.no_l%_pred%.pcnt_qt% from INFO tables layer_pcnts%.no_l% (killed
/* at end) and total_pumpage.  It calculates the vertical distribution of
/* total pumpage (in -ft3/s) for both the reported and predictive period
/* and adjusts (as specified in the menu) predictive pumpage (1997-2027)
/* to simulate future increases and (or) decreases in pumpage.  For each
/* well, a single record is saved from each contributing layer and for all
/* years modeled (1945-2027).

/*
/*    where:   q(n) = QT * pcnt(n)
/*          q(n) = total pumpage assigned to layer n (-ft3/s)
/*             n = is the model-layer number
/*            QT = total pumpage of well (-ft3/s)
/*       pcnt(n) = percentage of total pumpage assigned to model layer n
/*
/* Total pumpage for reported years 1945-96 is calculated as:
/*            QT = Yr * -.0013813 (ft3/s)/acre-ft
/*
/* Total pumpage for predictive years 1997-2027 is calculated as:
/*            QT = Yr * -.0013813 (ft3/s)/acre-ft * pcnt_qt / 100
```

```
/*    where:  Yr = total pumpage of well (acre-ft)
/*       pcnt_qt = percentage of total to be used in the MODFLOW modeling
/*                                                                  run.
/*
/*     "Pump_out" creates the MODFLOW-readable flat file (ft3/s).  It
/* reads from QT_%.no_l%_pred%.pcnt_qt% and calculates net pumpage (-ft3/s)
/* for all years in the simulation period.  These net pumpage values of
/* vertically distributed data are unloaded along with data from INFO tables
/* containing +Q, including (+Q) art_rchg_ann, rchg_mtn_ann, uf_lytle_ann,
/* and uf_bh_ann.  Data are unloaded in order of ascending stress period
/* and model-layer number.
/*
/*     where: q(net) = q(n) * pcnt_ir / 100
/*
/*           pcnt_ir = irrigation efficiency (remainder is return flow).
/*
/*
/* --------------------------------------------------------------------------
/* History:
/* Author/Site      Date      Version    Event
/* --------------------------------------------------------------------------
/* kmkoczot       6/30/95      1.0       pump_out.aml written for
/*                                             Masters thesis.   Unloads
/*                                             pumpage and recharge into
/*                                             MODFLOW readable format.
/* kmkoczot       8/19/96      2.0       pump_out.aml modified for Mojave
/*                                             MODFLOW model.
/* kmkoczot       7/17/97      ---       calc_perfs.aml  first cut written
/* kmkoczot       7/18/97      ---       calc_qn.aml   first cut written
/* kmkoczot       8/24/97      3.0       pump_out.aml modified for Rialto-
/*                                             Colton MODFLOW model.
/* kmkoczot        2/8/98      1.0       calc_perfs.aml  revision
/* kmkoczot        2/9/98      1.0       calc_pcnt.aml   written
/* kmkoczot       2/11/98      1.0       calc_qn.aml   revision
/* kmkoczot       2/12/98      3.1       pump_out.aml revision
/* kmkoczot        5/4/98      ---       four amls revised to create
/*                                             four-layer model output.
/* kmkoczot        5/6/98      ---       four amls revised to create
/*                                             five-layer model output.
/* kmkoczot        5/6/98      ---       pumpall_4amls.aml catenated amls
/*                                             above into this program
/*                                             to make four-layer output.
/* kmkoczot        6/2/98      ---       pumpall_4amls.aml revised to read
/*                                             from files of years. Aml
/*                                             sections revised and added
/*                                             as routines. **Output is
/*                                             for four layers.
/* kmkoczot       8/11/98      ---       four amls creating five-layer
/*                                             output revised as routines.
/* kmkoczot       8/13/98      ---       mk_wellpkg.aml  revised above
/*                                             "pumpall_4amls.aml", to
/*                                             include five-layer routines.
/*                                             Renamed as this program.
/*                                          (**four and five-layer output).
```

```
/* kmkoczot       8/19/98      ---       mk_wellpkg.aml revised to allow
/*                                             output of percentages of
/*                                             total pumpage (for use in
/*                                             predictive modeling runs).
/* kmkoczot       8/21/98      ---       mk_wellpkg.aml revised to use
/*                                             out.menu.
/* kmkoczot        3/3/99      ---       mk_wellpkg.aml revised to send
/*                                             warning to screen if
/*                                             working files are missing.
/* kmkoczot       3/23/99      ---       mk_wellpkg.aml revised to use
/*                                             wellpkg.menu.
/* kmkoczot       8/99         1.0       mk_wellpkg.aml revised to use new
/*                                             wellpkg.menu which allows the
/*                                             simulation period to be
/*                                             entered.   No no longer
/*                                             reads from files of years.
/*                                             Modified some routines to
/*                                             reduce processing time.
/*                                             Added variable and routine
/*                                             descriptions to header. Added
/*                                             comment lines to coding.
/*                                             (Final coding)
/*
/*----------------------------------------------------------------------------
/*
/* Disclaimer:
/*   Although this program has been used by the U.S. Geological Survey, no
/* warranty, expressed or implied, is made by the USGS as to the accuracy
/* and functioning of the program and related program material nor shall the
/* fact of distribution constitute any such warranty, and no responsibility
/* is assumed by the USGS in connection herewith.
/*
/*============================================================================

/*-- Begin mk_wellpkg.aml.
&severity &error &routine bailout_rtne
&terminal 9999
/* Call menu.
 &menu wellpkg.menu &form &stripe 'MAKE WELL PACKAGE'
    &if %.exit_pgm%  &then &return Exiting Program Mk_wellpkg.aml
    &messages &off &all
  /* Verify the INFO tables and flat files exist to make output.
  &call check_settings

/* Begin computing.
&type [quote MAKING WELL-PACKAGE FOR %.qtype% CONDITIONS ~
WITH %.no_l% MODEL LAYERS.]
&type [quote FOR YEARS    BEGIN: %.b_year%  END: %.e_year%]
&type [quote USING %.pcnt_ir% PERCENT OF TOTAL PUMPAGE FOR NET CALCULATIONS]
&type [quote AND %.pcnt_qt% PERCENT OF TOTAL PUMPAGE FOR PREDICTIVE ~
CALCULATIONS.]
&type ' '
&type [quote CALCING LENGTH OF PERFORATED INTERVAL IN EACH LAYER...]
  &call calc_perfs
```

```
&type [quote CALCING PERCENT OF TOTAL PUMPAGE FROM EACH LAYER...]
  &call calc_pcnt
&type [quote CALCING RATE OF NET PUMPAGE (-ft3/s) FROM EACH LAYER...]
  &call calc_qn
  &call pump_out
&type [quote .     FINISHED  :>  .]
&type ~
   [quote YOUR NEW WELL-PACKAGE FILE IS: %.mfile%.dat .]
    &messages &on
&return   /* closes mk_wellpkg.aml


/*----------------------ROUTINES--------------------------------------------
/*---------------------bailout_rtne
&routine bailout_rtne
 &severity &error &ignore
  &if [quote [translate [show program]]] = 'TABLES' &then QUIT
   &s .exit_pgm = .true.
    &messages &on
    &type 'An error has occurred in mk_wellpkg.aml.'
     &if %.exit_pgm%  &then &return Exiting Program Mk_wellpkg.aml
    &call cleanup_rtne
&return  /* closes bailout_rtne


/*---------------------check_settings
&routine check_settings
/* verify the user has write permission to the current workspace
 &if not [access [show workspace] -write] &then
    &do
      &type;&type Warning!! User [upcase [username]] does not have write ~
            permissions
      &type to the current workspace. The program has been canceled.
      &return
    &end  /* if-then-do

/* verify the current directory is an arc/info workspace
 &if not [exists [show workspace] -workspace] &then
    &do
      &s tempcov = [scratchname -dir]
      create %tempcov%
      kill %tempcov% all  /* this leaves the needed INFO subdirectory.
    &end  /* if-then-do

/* Verify the existence of INFO tables.
  &do i_f &list WELL_KS_%.no_l% art_rchg_ann rchg_mtn_ann ~
                uf_lytle_ann uf_bh_ann layer_alt_%.no_l% ~
                well_perfs_%.no_l%  well_rowcol total_pumpage
   &if ^ [exists %i_f% -info] &then
     &do
       &type [quote Missing INFO File: %i_f%]
       &type 'Please create using Load_data.aml .'
       &s .exit_pgm = .true.
       &messages &on
```

```
        &if %.exit_pgm%  &then &return Exiting Program Mk_wellpkg.aml
     &end   /* if-then-do
  &end  /* do-if-then

&return  /* closes check_settings routine.


/*---------------------calc_perfs
&routine calc_perfs
/* For active cells only, find perf lengths and active layer n for
/* each well, unless already specified in INFO table: well_perfs_%.no_l%.

/* Calculates length of well perf interval for layer n.
/*      makes INFO table: layer_perfs%.no_l%
/* which is populated with perf lengths for each wellid.

/* Verify cleanup of directory.
  &do f &list work.csv f.wcsv layer_perfs%.no_l% temp2
    &if [exists %f% -info] &then &s junk [delete %f% -info]
  &end  /* do-if-then
  &do f &list temp.dat fix loadok lp_wellids
    &if [exists %f%] &then &s junk [delete %f%]
  &end  /* do-if-then

/*-- Begin length calculations.
TABLES
/* Note: layer_alt_%.no_l% contains model top(n) and bot(n) altitudes.
  &if ^ [iteminfo layer_alt_%.no_l% -info wellid -indexed] &then
           indexitem layer_alt_%.no_l% wellid
  relate add r.1 layer_alt_%.no_l% info wellid wellid linear auto

/* Perf lengths are computed for layer n based on seven assumptions:
/* 1) layer n is not active at perfs.
/* 2) perfs are not in layer n.
/* 3) top_ele ge top(n) and bop_ele lt top(n) and bop_ele ge bot(n).
/* 4) top_ele le top(n) and bop_ele ge bot(n).
/* 5) top_ele le top(n) and top_ele gt bot(n) and bop_ele le bot(n).
/* 6) top_ele ge top(n) and bop_ele le bot(n).
/* 7) model layer was loaded (along with other data) into
/*         well_perfs_%.no_l%.  Therefore, record ignored.

  copy well_perfs_%.no_l%  work.csv
  additem work.csv active 2 2 i
    &do n = [unquote 1 &to %.no_l% &by 1 ]
      additem work.csv d3_%n% 9 9 n 2
      additem work.csv d4_%n% 9 9 n 2
      additem work.csv d5_%n% 9 9 n 2
      additem work.csv d6_%n% 9 9 n 2
    &end  /* do
  sel work.csv

/* Compute perf lengths in active layer n.
  &do n = [unquote 1 &to %.no_l% &by 1 ]
    /*  For assumption #7 above:
```

```
    /*      remove records with set layer/pcnt contribution.
        resel layer lt 1
    /* Find records in active layers.  Flag working records.
        resel r.1//top%n% ne -99 and r.1//bot%n% ne -99
        calc active = 1

    /* Compute for #3 assumption above.
    resel top_ele ge r.1//top%n% and bop_ele lt r.1//top%n% and ~
    bop_ele ge r.1//bot%n%
      /* and since anything above top%n% is not considered...
      calc d3_%n% = r.1//top%n% - bop_ele
    commit

    /* Compute for #4 assumption above.
    resel active = 1
    resel top_ele le r.1//top%n% and bop_ele ge r.1//bot%n%
    calc d4_%n% = top_ele - bop_ele
    commit

    /* Compute for #5 assumption above.
    resel active = 1
    resel top_ele le r.1//top%n% and top_ele gt r.1//bot%n% and ~
    bop_ele le r.1//bot%n%
      /* and since anything below bot%n% is not considered...
      calc d5_%n% = top_ele - r.1//bot%n%
    commit

    /* Compute for #6 assumption above.
    resel active = 1
    resel top_ele ge r.1//top%n% and bop_ele le r.1//bot%n%
      /* and since anything outside layer is not considered...
      calc d6_%n% = r.1//top%n% - r.1//bot%n%
    commit

    calc active = 0
    commit
  &end  /* do
QUIT /*TABLES

&call mk_layer_perfs%.no_l%

  &do n = [unquote 1 &to %.no_l% &by 1 ]
    additem layer_perfs%.no_l% d3_%n% 9 9 n 2
    additem layer_perfs%.no_l% d4_%n% 9 9 n 2
    additem layer_perfs%.no_l% d5_%n% 9 9 n 2
    additem layer_perfs%.no_l% d6_%n% 9 9 n 2
  &end  /* do

  sel layer_perfs%.no_l%
  add from temp.dat
  commit
  sel

  &do n = [unquote 1 &to %.no_l% &by 1 ]
```

```
    additem layer_perfs%.no_l% L%n% 9 9 n 2
  &end  /* do

  sel layer_perfs%.no_l%
  &do n = [unquote 1 &to %.no_l% &by 1 ]
    calc L%n% = d3_%n% + d4_%n% + d5_%n% + d6_%n%
    commit
  &end  /* do
  sel
/*-- End length calculations.

/*-- Load new layer(s) for each well.
/* Prepare layer_perfs%.no_l% for new layer data.
  additem layer_perfs%.no_l% layer_temp 5 10 i # layer
    &do n = [unquote 1 &to %.no_l% &by 1 ]
      additem layer_perfs%.no_l% layer%n% 1 1 i
    &end  /* do

  sel layer_perfs%.no_l%
    &do n = [unquote 1 &to %.no_l% &by 1 ]
      resel L%n% gt 0
      calc layer%n% = %n%
      commit
    &end  /* do

  &call redefine_%.no_l%_rtne

  resel junk_layer gt 0
  unload lp_wellids wellid
  unload fix junk_layer
  commit
  sel
QUIT /*TABLES

/* Edit temporary file.
  &data vi fix > /dev/null
    :g/0/s///g
    :wq
  &end   /* data
  &sys paste -d',' lp_wellids fix > loadok

TABLES
  define temp2
    wellid 15 15 c
    layer 5 10 i
  ~
  add from loadok
  commit
  sort wellid
  commit

  relate add r.2 temp2 info wellid wellid ordered auto

  sel layer_perfs%.no_l%
```

```
    resel wellid = r.2//wellid
    calc layer_temp = r.2//layer
  commit
    resel layer_temp gt 0
    calc layer = layer_temp
  commit
QUIT /*TABLES

/*-- End new layers.

/* clean up directory
  &do f &list temp.dat fix loadok lp_wellids
   &if [exists %f%] &then &s junk [delete %f%]
  &end  /* do-if-then
  &do f &list temp2 work.csv f.wcsv
   &if [exists %f% -info] &then &s junk [delete %f% -info]
  &end  /* do-if-then
  &do n = [unquote 1 &to %.no_l% &by 1 ]
   dropitem layer_perfs%.no_l% layer_perfs%.no_l% layer%n%
  &end  /* do
&call clean_layer_perfs%.no_l%
&return  /* closes calc_perfs


/*---------------------mk_layer_perfs4
&routine mk_layer_perfs4
  frequency work.csv f.wcsv
    wellid
    layer
    PCNT1
    PCNT2
    PCNT3
    PCNT4
    end
    d3_1
    d4_1
    d5_1
    d6_1
    d3_2
    d4_2
    d5_2
    d6_2
    d3_3
    d4_3
    d5_3
    d6_3
    d3_4
    d4_4
    d5_4
    d6_4
    end

TABLES
  sel f.wcsv
```

```
  unload temp.dat wellid layer PCNT1 PCNT2 PCNT3 PCNT4 ~
     d3_1 d4_1 d5_1 d6_1 d3_2 d4_2 d5_2 d6_2 d3_3 d4_3 d5_3 d6_3 ~
     d3_4 d4_4 d5_4 d6_4
  sel
  define layer_perfs%.no_l%
    wellid 15 15 c
    layer 5 10 i
    PCNT1  7 9 N 5
    PCNT2  7 9 N 5
    PCNT3  7 9 N 5
    PCNT4  7 9 N 5
  ~
  sel
&return  /* closes mk_layer_perfs4


/*---------------------mk_layer_perfs5
&routine mk_layer_perfs5
  frequency work.csv f.wcsv
    wellid
    layer
    PCNT1
    PCNT2
    PCNT3
    PCNT4
    PCNT5
    end
    d3_1
    d4_1
    d5_1
    d6_1
    d3_2
    d4_2
    d5_2
    d6_2
    d3_3
    d4_3
    d5_3
    d6_3
    d3_4
    d4_4
    d5_4
    d6_4
    d3_5
    d4_5
    d5_5
    d6_5
    end

TABLES
  sel f.wcsv
  unload temp.dat wellid layer PCNT1 PCNT2 PCNT3 PCNT4 PCNT5 ~
    d3_1 d4_1 d5_1 d6_1 d3_2 d4_2 d5_2 d6_2 d3_3 d4_3 d5_3 d6_3 ~
    d3_4 d4_4 d5_4 d6_4 d3_5 d4_5 d5_5 d6_5
```

```
  sel
  define layer_perfs%.no_l%
    wellid 15 15 c
    layer 5 10 i
    PCNT1  7 9 N 5
    PCNT2  7 9 N 5
    PCNT3  7 9 N 5
    PCNT4  7 9 N 5
    PCNT5  7 9 N 5
  ~
  sel
&return  /* closes mk_layer_perfs5


/*---------------------redefine_4_rtne
&routine redefine_4_rtne
redefine
  234
  junk_layer 4 4 I
~
&return  /* closes redefine_4_rtne


/*---------------------redefine_5_rtne
&routine redefine_5_rtne
redefine
  286
  junk_layer 5 5 I
~
&return  /* closes redefine_5_rtne


/*---------------------clean_layer_perfs4
&routine clean_layer_perfs4
  &do i &list D3_1 D4_1 D5_1 D6_1 D3_2 D4_2 D5_2 D6_2 D3_3 D4_3 D5_3 D6_3 ~
      D3_4 D4_4 D5_4 D6_4
     dropitem layer_perfs%.no_l% layer_perfs%.no_l% %i%
  &end  /* do
&return  /* closes clean_layer_perfs4


/*---------------------clean_layer_perfs5
&routine clean_layer_perfs5
  &do i &list D3_1 D4_1 D5_1 D6_1 D3_2 D4_2 D5_2 D6_2 D3_3 D4_3 D5_3 D6_3 ~
      D3_4 D4_4 D5_4 D6_4 D3_5 D4_5 D5_5 D6_5
     dropitem layer_perfs%.no_l% layer_perfs%.no_l% %i%
  &end  /* do
&return  /* closes clean_layer_perfs5


/*---------------------calc_pcnt
&routine calc_pcnt
/* calcs percent of total pumpage from layer n
```

```
/*      makes INFO table: layer_pcnts%.no_l%
/*      kills INFO table: layer_perfs%.no_l%
/* where: k(n) = hydraulic conductivity of layer n (ft/sec)
/*        pcnt(n) = L(n) * k(n) / L1*k1 + L2*k2 ... + L(n)*k(n)
/*        pcnt(n) = percentage of total pumpage from layer n
/*                                        (representative fraction)

/*-- Verify cleanup of directory.
&if [exists layer_pcnts%.no_l% -info] &then &s junk ~
                [delete layer_pcnts%.no_l% -info]

TABLES
/*-- Begin percent calcs based on perf. interval length and K(n).
  &if ^ [iteminfo well_Ks_%.no_l% -info wellid -indexed] &then
           indexitem well_Ks_%.no_l% wellid
  relate add r.1 well_Ks_%.no_l% info wellid wellid linear auto

  /* Set up file to receive new percent value for each layer.
  copy layer_perfs%.no_l% layer_pcnts%.no_l%

  /* Items L(n) and k(n) come from other files and are related by wellid.
  additem layer_pcnts%.no_l% denom 11 11 N 7

  sel layer_pcnts%.no_l%

  /* Calculate pcnt%n% for each layer.
   &call calc_denom%.no_l%
     resel layer_temp gt 0
     resel denom ne 0 /* verify the denominator is not equal to zero.
         &do n = [unquote 1 &to %.no_l% &by 1 ]
           calc pcnt%n% = L%n% * r.1//k%n% / denom
         &end  /* if-then-do
   commit

  /* Calc pcnt(n) for wells perfed in one layer.
    &do n = [unquote 1 &to %.no_l% &by 1 ]
      resel layer_temp lt 1
      resel layer = %n%
      calc pcnt%n% = 1
      commit
    &end  /* do

  kill layer_perfs%.no_l%
QUIT /*TABLES

/*-- End percent calcs based on perf. interval length and K(n).

/* clean up directory
dropitem layer_pcnts%.no_l% layer_pcnts%.no_l% denom
&return  /* closes calc_pcnt


/*---------------------calc_denom4
```

```
&routine calc_denom4
/* calc pcnt(n)
calc denom = L1 * r.1//k1 + L2 * r.1//k2 + L3 * r.1//k3 + L4 * r.1//k4
&return  /* closes calc_denom4


/*---------------------calc_denom5
&routine calc_denom5
/* calc pcnt(n)
calc denom = L1 * r.1//k1 + L2 * r.1//k2 + L3 * r.1//k3 + L4 * r.1//k4 ~
             + L5 * r.1//k5
&return  /* closes calc_denom5


/*---------------------calc_qn
&routine calc_qn
/* Calculates total pumpage (-ft3/s) from each layer for each well.
/*     where: q(n) = QT * pcnt(n)
/*            q(n) = total pumpage assigned to layer n (-ft3/s)
/*            QT = total pumpage of well (-ft3/s)
/*      makes INFO table: QT_%.no_l%_pred%.pcnt_qt%
/*      kills INFO table: layer_pcnts%.no_l%

/* Verify directory cleanup.
  &do f &list QT_%.no_l%_pred%.pcnt_qt% pumpage_temp
     &if [exists %f% -info] &then &s junk [delete %f% -info]
  &end  /* do-if-then
  &if [exists load_this] &then &s junk [delete load_this]

copyinfo total_pumpage pumpage_temp

TABLES
  &if ^ [iteminfo layer_pcnts%.no_l% -info wellid -indexed] &then
           indexitem layer_pcnts%.no_l% wellid
  relate add r.1 layer_pcnts%.no_l% info wellid wellid linear auto

  &if ^ [iteminfo well_rowcol -info wellid -indexed] &then
           indexitem well_rowcol wellid
  relate add r.2 well_rowcol info wellid wellid linear auto

/*-- Calcs one layer at a time (all years). Dumps to flat file: load_this.
/*-- Data in "load_this" are added to INFO table: QT_%.no_l%_pred%.pcnt_qt%.

  /* Set up pumpage_temp for calculations.
    &do yr = 1945 &to 2027 &by 1
      additem pumpage_temp Y%yr%qn 10 10 n 6 Y%yr%
    &end  /* do
    additem pumpage_temp QT 10 10 N 6

  /* Add and update row column cell (=rowcol) items with current data.
        additem pumpage_temp layer 5 10 I # otherid2
        additem pumpage_temp row 4 10 I # layer
        additem pumpage_temp col 4 10 I # row
        additem pumpage_temp cell 8 8 I # col
     sel pumpage_temp
```

```
        resel wellid = r.2//wellid
        calc cell = r.2//cell
        calc row = r.2//row
        calc col = r.2//col
     sel

/*-- Begin calcs of net pumpage (qn) by well for layer n.

   sel pumpage_temp
     &do n = [unquote 1 &to %.no_l% &by 1 ]
       calc layer = %n%

       /* For the Reported Period:
         /* Converts total pumpage in acre-ft to -ft3/s (MODFLOW discharge).
           &do yr = 1945 &to 1996 &by 1
              calc qt = ( Y%yr% * -.0013813 )
             /*  Calculate vertical total pumpage
               calc Y%yr%qn = qt * r.1//pcnt%n%
               calc qt = 0
           &end  /* do

       /* For the Predictive Period:
         /* Converts total pumpage in acre-ft to -ft3/s (MODFLOW discharge)
         /* and adjusts total pumpage to the percentage set in the menu
         /* to test the predictive scenario of interest.
            &do yr = 1997 &to 2027 &by 1
              calc qt = ( Y%yr% * -.0013813 ) * ( %.pcnt_qt% / 100 )
              /* Calculate vertical net pumpage
                calc Y%yr%qn = qt * r.1//pcnt%n%
                calc qt = 0
           &end  /* do

         /* unload predictive data.
           &s unload_years = Y1945qn
           &do n = 1946 &to 2027 &by 1
              &s unload_years = %unload_years% Y%n%qn
           &end  /* do
            unload load_this WELLID otherid1 otherid2 layer row col cell ~
              %unload_years%
            commit

       /* set items back to zero.
       calc qt = 0
       calc layer = 0
       commit
     &end  /* do
/*-- End calcs of q(n) for each layer.

   /* Set up file to receive computed data.
   define QT_%.no_l%_pred%.pcnt_qt%
     WELLID              15    15     C
     OTHERID1            15    15     C
     OTHERID2            15    15     C
     LAYER                5    10     I
```

```
    ROW                    4    10     I
    COL                    4    10     I
    CELL                   8     8     I
  ~
  sel
  &do yr = 1945 &to 2027 &by 1
     additem QT_%.no_l%_pred%.pcnt_qt% Y%yr% 10 10 n 6
  &end  /* do

  /* Load data into new INFO table.
  sel QT_%.no_l%_pred%.pcnt_qt%
  add from load_this
  commit

  sel
QUIT /*TABLES

/* Clean up directory.
  &do f &list pumpage_temp layer_pcnts%.no_l%
    &if [exists %f% -info] &then &s junk [delete %f% -info]
  &end  /* do-if-then
  &if [exists load_this] &then &s junk [delete load_this]

&return  /* closes calc_qn


/*---------------------pump_out
&routine pump_out
/* This unloads INFO table data to the well-package flat file
/* in MODFLOW format, for initial, transient, or predictive
/* time series.
/* format =:  layer(10f) row(10f) col(10f) Qn(10f) comment_lines

/* Variables below set in wellpkg.menu.
/* for initial-conditions  .mfile = initial
/* for transient   .mfile = transient
/* for predictive  .mfile = predictive
/* Irrigation efficiency .pcnt_ir = .70 (example)

/* reading from INFO tables:
/* QT_%.no_l%_pred%.pcnt_qt%  -- annual -Q in ft3/s by layer
/* uf_lytle_ann  -- annual +Q in ft3/s by layer
/* uf_bh_ann    -- annual +Q in ft3/s by layer
/* rchg_mtn_ann  -- annual +Q in ft3/s by layer
/* art_rchg_ann  -- annual +Q in ft3/s by layer

&call cleanup_pump_out /* in case program bombed before.

TABLES
/*--Set MODFLOW file name.
  &if %.qtype% cn 'predict' &then
     &s .mfile = %.qtype%_%.no_l%_p%.pcnt_qt%_n%.pcnt_ir%
     &else  &do
        &s .mfile = %.qtype%_%.no_l%_n%.pcnt_ir%
```

```
  &end  /* if-then-else-do
    &if [exists %.mfile%.dat] &then &s junk [delete %.mfile%.dat]
    &type [quote UNLOADING -Q AND +Q TO MODFLOW FILE %.mfile%.dat.]

/*-- Prepare INFO tables for calculations.
  /* Add temporary items to INFO tables.
    &do X &list QT_%.no_l%_pred%.pcnt_qt% uf_lytle_ann uf_bh_ann ~
         rchg_mtn_ann art_rchg_ann
      additem %X% temp1 15 15 c
      additem %X% space 1 1 c
    &end  /* do

  /* Add another temporary item to QT_%.no_l%_pred%.pcnt_qt%.
  additem QT_%.no_l%_pred%.pcnt_qt% pumpage_a 10 10 n 6

/*-- Calculate irrigation efficiency rate.
   &s .IR = [unquote %.pcnt_ir% / 100 ]


/*-- Output stress period net pumpage.
  /* Set header line
   &s header = '   287       40'

  /* Unload header to MODFLOW format.
  sel QT_%.no_l%_pred%.pcnt_qt%
  resel $recno = 1
  unload %.mfile%.dat [quote %header%] columnar junk1
  commit

  /* Set years of data to unload to well-package flat file.
    &do .date = %.b_year% &to %.e_year% &by 1  /* simulation period.
      &s Y = Y%.date%
        /* Calculate -Q net, taking out return flow.
        sel QT_%.no_l%_pred%.pcnt_qt%
        calc pumpage_a  = %Y% * %.IR%
        commit
        sel

        /* Count number of records by stress period that are in an active
        /*   cell and -Q lt 0.
        sel QT_%.no_l%_pred%.pcnt_qt%
        move [quote [unquote '_']%Y%] to temp1
        sort cell wellid
        resel %Y% lt 0 and cell gt 0 and layer gt 0
        show number select
         &s C1 = [show number select]
        commit

        &do X &list uf_lytle_ann uf_bh_ann rchg_mtn_ann art_rchg_ann
          /* Count no. of recs = active cell and +Q lt 0 per stress period.
          sel %X%
          &s name = %X%
           move [quote _%name%] to temp1
           resel %Y% gt 0
```

```
          show number select
            &s C%X% = [show number select]
        &end  /* do

        &s C3 = %C1% + %Cuf_lytle_ann% + %Cuf_bh_ann% + %Crchg_mtn_ann% ~
                 + %Cart_rchg_ann%

        &if %C3% < 10 &then ~
        &s headvar = [quote %C3%                                        %Y%]
        &else &if %C3% < 100 &then ~
        &s headvar = [quote %C3%                                        %Y%]
        &else &if %C3% < 1000 &then ~
        &s headvar = [quote %C3%                                        %Y%]
        &else ~
        &s headvar = [quote %C3%                                        %Y%]
        commit

        /* Unload header and record count to MODFLOW format.
        sel QT_%.no_l%_pred%.pcnt_qt%
        commit
        resel $recno = 1
        unload %.mfile%.dat [quote %headvar%] columnar junk1
        commit

        /* Unload data to MODFLOW format.
        &do n = [unquote 1 &to %.no_l% &by 1 ]
          sel QT_%.no_l%_pred%.pcnt_qt%
          resel %Y% lt 0 and cell gt 0 and layer = %n%
          unload %.mfile%.dat layer row col pumpage_a temp1 space wellid ~
               space otherid1 columnar junk1
          commit

           &do X &list uf_lytle_ann uf_bh_ann rchg_mtn_ann art_rchg_ann
              sel %X%
              resel %Y% gt 0 and cell gt 0 and layer = %n%
              unload %.mfile%.dat layer row col [quote %Y%] temp1 space ~
                cell columnar junk1
              commit
           &end  /* do
        &end  /* do
    &end  /* do

/* Close the file with years to calculate data for.
&type [close -all]
QUIT /*TABLES

/* clean up directory
&call cleanup_pump_out
&return  /* closes pump_out


/*----------------------cleanup_pump_out
&routine cleanup_pump_out
 &if [exists junk1 -file] &then &s junk [delete junk1 -file]
```

```
   &do X &list QT_%.no_l%_pred%.pcnt_qt% uf_lytle_ann uf_bh_ann ~
      rchg_mtn_ann art_rchg_ann
      dropitem %X% %X%
      temp1
      space
      end
   &end  /* do

dropitem QT_%.no_l%_pred%.pcnt_qt% QT_%.no_l%_pred%.pcnt_qt% pumpage_a
&return  /* closes cleanup


/*---------------------cleanup_rtne
&routine cleanup_rtne
/* close all global variables set by this program.
  &dv .QTYPE .b_year .e_year .no_l .pcnt_ir .pcnt_qt .exit_pgm ~
       .mfile .IR .date
 /* close routines set by this program.
  &if ^ [null [show relates]] &then &do
     relate drop;r.1;;
     relate drop;r.2;;
  &end /* if-then-do

 &return  /* closes cleanup_rtne

/*---------------------end of routines.
```