Geohydrology and Simulated Response to Ground-Water Pumpage in Carson Valley, A River-Dominated Basin in Douglas County, Nevada, and Alpine County, California

By Douglas K. Maurer

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[Plates are in pocket]

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CONVERSION FACTORS AND ABBREVIATIONS

"Inch-pound" units of measure used in this report may be converted to International System (metric) units by using the following factors:

Multiply	*By*	*To obtain*
Acres	0.4047	Square hectometers (hm^2)
Acre-feet (acre-ft)	0.001233	Cubic hectometers (hm^3)
Acre-feet per year (acre-ft/yr)	0.001233	Cubic hectometers per year (hm^3/yr)
Cubic feet per second (ft^3/s)	0.02832	Cubic meters per second (m^3/s)
Feet (ft)	0.3048	Meters (m)
Feet per mile (ft/mi)	0.1894	Meters per kilometer (m/km)
Feet per second (ft/s)	0.3048	Meters per second (m/s)
Feet per year (ft/yr)	0.3048	Meters per year (m/yr)
Inches (in.)	25.40	Millimeters (mm)
Miles (mi)	1.609	Kilometers (km)
Square feet (ft^2)	0.0929	Square meters (m^2)

For temperature, degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) by using the formula °C = 0.5556 (°F - 32).

NATIONAL GEODETIC VERTICAL DATUM OF 1929

The term "National Geodetic Vertical Datum of 1929" (NGVD of 1929) replaces the formerly used term "mean sea level" to describe the datum for altitude measurements. The geodetic datum is derived from a general adjustment of the first-order leveling networks in both the United States and Canada. For convenience in this report, the datum also is referred to as "sea level."

GEOHYDROLOGY AND SIMULATED RESPONSE TO GROUND-WATER PUMPAGE IN CARSON VALLEY, A RIVER-DOMINATED BASIN IN DOUGLAS COUNTY, NEVADA, AND ALPINE COUNTY, CALIFORNIA

By Douglas K. Maurer

ABSTRACT

A numerical model was used to simulate the effect of development of the ground-water reservoir in Carson Valley on Carson River outflow, evapotranspiration, and ground-water levels and storage. Flood irrigation from flow of the Carson River is the main source of water for agriculture in the valley. Geohydrologic data from previous reports and drillers' logs were combined with water-level and streamflow measurements for water years 1981-83 to produce a comprehensive characterization of the hydrologic system.

The basin-fill ground-water reservoir consists of: (1) confined and unconfined sedimentary deposits of Quaternary age that underlie the valley floor, and (2) sedimentary deposits of Tertiary age that are exposed mainly on the east side of the valley. Water-levels indicate the presence of two confined aquifer systems: one relatively shallow--less than 100 feet deep--that lies along the base of the Carson Range on the west side of the valley, and the other--generally deeper than 200 feet--that underlies most of the western half of the valley floor. Unconfined water levels are within 5 feet of land surface throughout most of the valley floor, the depth to water increasing to over 100 feet near the margins of the valley. The Tertiary sediments transmit water mainly through thin sand and gravel strata separated by thick, partly consolidated clay units, giving the deposits as a whole low hydraulic conductivity. The basin-fill reservoir is surrounded by granitic bedrock that transmits recharge to the basin through weathered and fractured zones near the contact between bedrock and valley fill.

Estimates were made of the distribution of hydraulic properties of aquifer materials, and of the components of inflow to and outflow from the basin-fill reservoir. Inflow components consisted of the following approximate quantities, in acre-feet per year: (1) mainstem Carson River flow, 360,000; (2) direct precipitation, 70,000; (3) runoff from perennial and ephemeral streams, 24,000; and (4) subsurface inflow, 38,000. Approximate estimates of outflow components were, in acre-feet per year: (1) mainstem Carson River flow, 291,000; and (2) potential evapotranspiration, 200,000. Both inflow and outflow totaled about 490,000 acre-feet per year. These flow volumes show that the hydrologic regimen of the basin is dominated by surface-water flow of the Carson River.

The estimates of hydraulic properties and water-budget components were incorporated into a numerical ground-water model that simulates evapotranspiration and interchange of water between the Carson River and the ground-water system of Carson Valley. Steady-state and transient calibration of the model provided an acceptable fit of observed versus simulated ground-water level fluctuations and storage, and surface-water outflow from the valley.

The steady-state simulation indicates net average annual losses of (1) about 44,000 acre-feet by surface-water percolation to the basin-fill reservoir, and (2) about 170,000 acre-feet by evapotranspiration and evaporation from surface-water bodies from the basin-fill reservoir. These values provide a reasonable balance for the simulated steady-state water budget.

Simulations show that surface-water flow is the ultimate source of about 75 percent of pumped water for six scenarios of possible future ground-water development. Simulated water-level declines due to pumping are small on the valley floor, where induced stream leakage replenishes the pumped water, but are greater near the east and west margins of the valley, where pumping intercepts subsurface recharge. In long-term (45-year) simulations, water-level declines due to pumping on the east and west sides of the valley extend to the valley floor with time, and additional stream leakage is induced. Model simulations indicate that changes from agricultural to urban land uses could decrease the loss of Carson River outflow to pumpage when streamflow is not used for flood irrigation in that area. However, accompanying permanent water-level declines would probably increase.

INTRODUCTION

Urban development of the ground-water basins along the eastern side of the Sierra Nevada is increasing the demand for ground-water supplies. Carson Valley is the major storage reservoir of potable ground water in the Carson River basin (Glancy and Katzer, 1975, p. 15). This ground water is the sole source of domestic and public supply for the rapidly expanding urban population in the valley, as well as a supplemental supply for agricultural production--a major economic base in the area.

Throughout the floor of Carson Valley, the Carson River is in intimate contact with the shallow ground-water reservoir, which lies within 5 feet of land surface. Increased ground-water withdrawals from the reservoir may decrease streamflow in the Carson River, which is a major source of water for agricultural use along the 50-mile reach downstream from Carson Valley. Large-scale ground-water withdrawals also may cause water-level declines and increase pumping lifts within Carson Valley.

Purpose and Scope

This investigation of the ground-water hydrology in Carson Valley was conducted from 1980 through 1985 by the U.S. Geological Survey, in cooperation with Douglas County. The purpose of the study was to (1) collect, compile, and analyze hydrologic data to quantify the hydrology of the valley and to enhance the understanding of the valley's geohydrologic system; and (2) develop a ground-water model that would simulate the response of the hydrologic system to applied stresses and that could be used to estimate the probable hydrologic effects of various development alternatives. This report presents the results of the investigation.

Work began with a gravity survey in 1980 to determine the depth to bedrock in Carson Valley; the results are discussed in detail in a separate publication (Maurer, 1986). From 1981 to 1983, work included: (1) measurement of water-level fluctuations and surface-water runoff, (2) drilling of additional observation wells, (3) collection of ground-water pumpage data and measurement of pump efficiencies, and (4) compilation of existing data reports and drillers' logs to obtain estimates of geohydrologic characteristics of the ground-water reservoir. Development of a water budget and initial estimates of hydraulic conductivities and specific yield were accomplished in 1983. From 1983 to 1985, the ground-water model was developed and calibrated, and simulations of possible ground-water development were made.

The model, which represents a compilation of all available data, was used to (1) test estimates of the geohydrologic characteristics of the ground-water reservoir, (2) evaluate the components of the water budget for the basin, (3) enhance the understanding of the hydrologic flow system in the basin, and (4) simulate the effect of various possible developmental alternatives on Carson River outflow, evapotranspiration, ground-water levels, and ground-water storage in the valley.

Description of Study Area

Figures 1 and 2, and plate 1 show the location and general features of Carson Valley. Almost all of the valley is in western Nevada, with its northern end about 4 miles south of Carson City, the State capital. The southwesternmost part of the valley is in Alpine County, Calif. Minden and Gardnerville are in the central part of the valley and the Johnson Lane, Indian Hills, and Jacks Valley subdivisions lie near the north end. The small town of Genoa and scattered small subdivisions lie along the west side of the valley. The small Ruhenstroth and Fish Spring Flat subdivisions are south and east of Gardnerville. Out of the total 284,000 acres in the drainage basin, 46,000 acres are irrigated for agricultural use. Approximately 6,000 acres of land are urban, supporting a population of about 25,000 (John Renz, Douglas County Planning Commission, written communication, 1983).

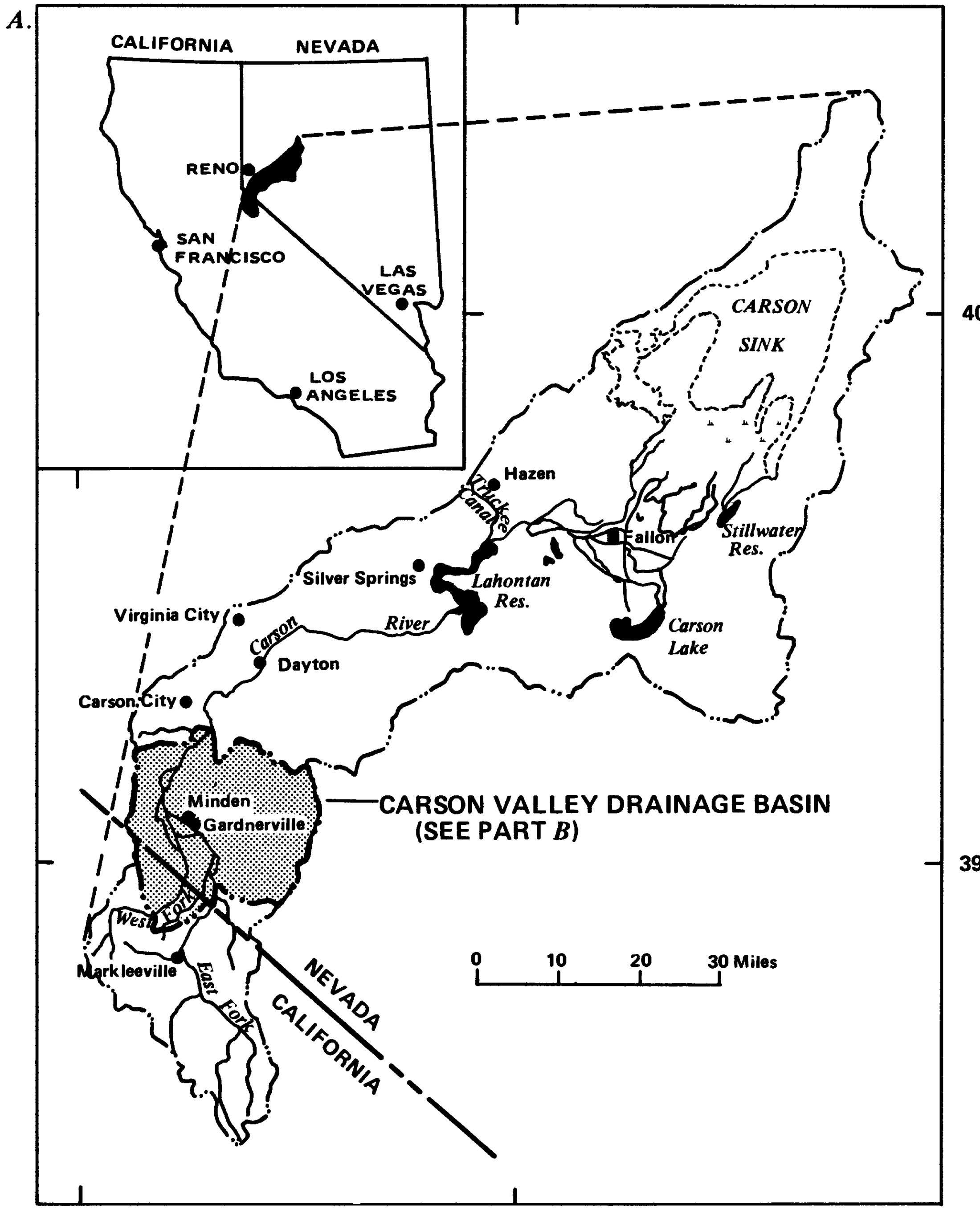
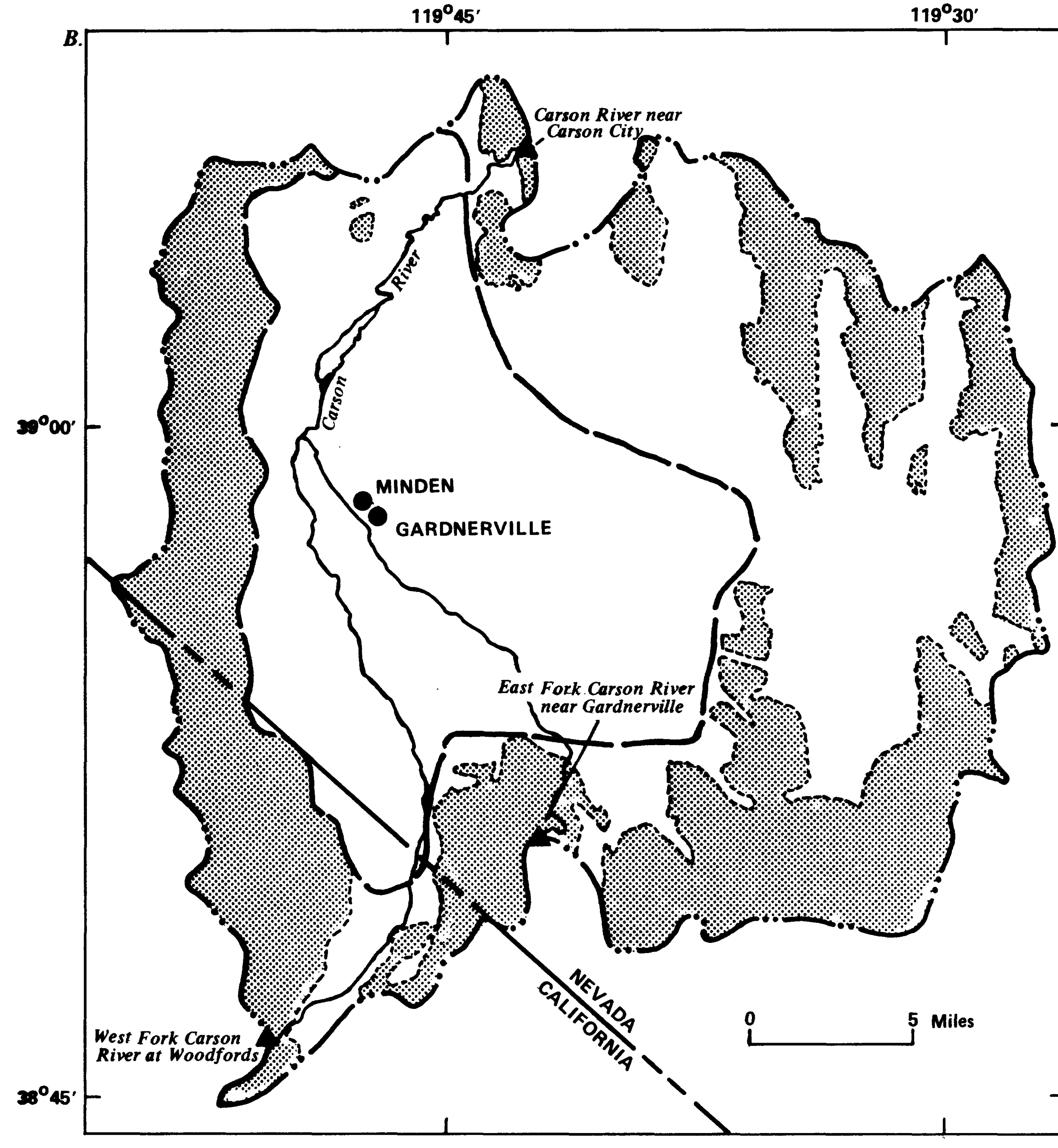


FIGURE 1.--Location of Carson River basin, Carson Valley drainage basin, and Carson Valley basin-fill reservoir.



EXPLANATION

BASIN-FILL DEPOSITS

BEDROCK

DRAINAGE-BASIN BOUNDARY

BOUNDARY OF BASIN-FILL RESERVOIR

STREAMFLOW GAGE AT DRAINAGE-BASIN BOUNDARY

FIGURE 1.--Continued.

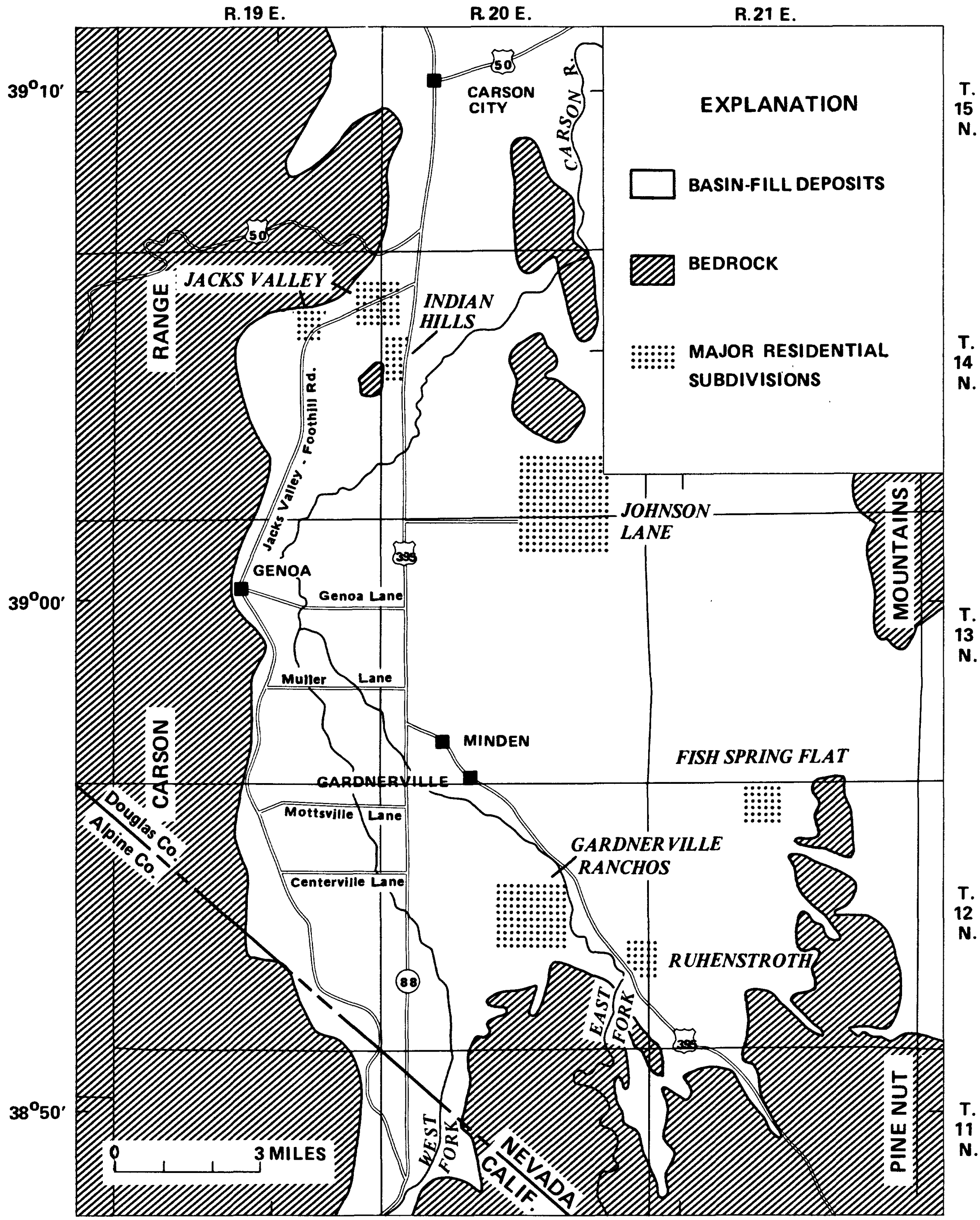


FIGURE 2.--Geographic features of Carson Valley.

Carson Valley is bounded by the Carson Range of the Sierra Nevada on the west and the Pine Nut Mountains on the east. The valley is oval shaped, 15 miles wide and 24 miles long; the valley floor slopes from an altitude of 5,000 feet above sea level in the south to 4,600 feet in the north. The Carson Range rises abruptly from the valley floor to a maximum altitude of about 10,000 feet, whereas the Pine Nut Mountains to the east rise more gradually to a maximum altitude of about 9,000 feet.

The valley lies in the rainshadow of the Sierra Nevada. The floor receives less than 10 inches of precipitation in an average year (plate 1). The Carson and Pine Nut Mountains, however, receive as much as 45 and 26 inches per average year, respectively; 92 percent of all precipitation is associated with winter storms from October to May and only 8 percent with summer thunderstorms (Spane, 1977, p. 47).

Summers in Carson Valley are warm; high temperatures are about 90 °F, with about 75 consecutive frost-free days, in an average year. Temperatures during winter months average about 30 °F, and the snow level often lowers to the valley floor.

The irrigated lands produce mainly alfalfa and native grass, which are used as forage for beef and dairy cattle as well as horses. The west side of the valley is flanked by steep alluvial fans vegetated with sage, bitterbrush, and rabbitbrush. Scrub vegetation gives way to Douglas fir on the steep slopes of the Carson Range. The east side of the valley is vegetated with sage and rabbitbrush, which are used mainly for sheep grazing; pinion pine becomes prominent at higher elevations, and is used mainly for firewood.

Previous Work

In the 1950's, a major dam (Watasheamu) was proposed on the East Fork Carson River south of the valley. Data for analysis of the possible effects of the dam were collected by the U.S. Bureau of Reclamation from 1950 to about 1960; the effort concluded with the compilation of several basic-data reports on the water levels and hydrologic setting of the valley by the U.S. Bureau of Reclamation (1954, 1961, 1965). From 1969 to 1977, several other reports were published on the water resources of Carson Valley which dealt with estimating various elements of the water budget of the valley: Piper (1969), Walters, Ball, Hibdon & Shaw (1970), Guitjens and Mahannah (1972), Vasey-Scott Engineering Company (1974), Glancy and Katzer (1975), and Spane (1977). Dillingham (1980) reviewed and evaluated previous work and provided much additional information on the hydrogeology of the ground-water reservoir.

Acknowledgments

The author is grateful to the residents of Carson Valley for their cooperation in the use of their private property for data collection; to Garry Stone of the Federal Watermaster's Office, the Sierra Pacific Power Co., and Lloyd Dillingham of the U.S. Bureau of Reclamation for their valuable technical contributions to this study; and to David E. Prudic, David L. Berger, and James R. Harrill of the U.S. Geological Survey for their valuable contributions to this investigation.

Definition of Ground-Water Terms

Hydraulic conductivity (K) is a property of an aquifer that determines the volume of water (Q) moving through a cross-sectional area (A) of aquifer material. In an aquifer with hydraulic conductivity equal in all directions and at all points (in hydrologic terms, an isotropic, homogeneous aquifer), water moves in response to, and parallel to, the slope of the water table or, in a confined aquifer, the hydraulic head. This slope is called the hydraulic gradient (I). On the basis of Darcy's law:

$$K = Q/IA ,$$

where K is expressed in feet per second, Q in cubic feet per second, A in square feet, and I in feet per foot. Hydraulic conductivity is roughly proportional to the grain size of the sediments in the aquifer--that is, large for sand and gravel and small for clay; however, it is also affected by sorting, grain packing, cementation, and grain roundness. The normal range for K in most aquifer materials is from a high value of about 0.03 ft/s for coarse gravel to a low value of about 0.000001 ft/s for silt (Freeze and Cherry, 1979, p. 29).

When hydraulic conductivity is multiplied by the thickness of the aquifer, the result is termed the aquifer transmissivity, T, in units of feet squared per second. Transmissivity is used in the flow equations of the numerical model developed in this report; however, input to the numerical model is in units of hydraulic conductivity, and the thickness of the aquifer is multiplied internally in the computer program. Thus, the term hydraulic conductivity, rather than transmissivity, is used throughout the remainder of this report.

Two types of aquifers are discussed in this report--confined and unconfined. In an unconfined aquifer, the water level in a well lies at the same altitude as the level of water saturation (the water table) in the aquifer. The altitude of the water level is called the hydraulic head (Freeze and Cherry, 1979, p. 20). In a confined aquifer, a fine-grained deposit of low hydraulic conductivity, known as a confining bed, overlies a saturated coarse-grained deposit of higher conductivity. Vertical flow is restricted by the confining bed, causing an increase in hydraulic pressure, or pressure head, in the underlying deposit. As a result, the water level in a well tapping the lower deposit rises above the top of that layer.

Sufficient pressure head may cause the water level to rise above land surface, resulting in a well that flows; this is commonly referred to as artesian flow.

Confining beds may be very low in conductivity, allowing little vertical flow, or leakage, or they may be only slightly less conductive than the underlying unit and intermittent in areal extent, resulting in considerable upward leakage.

The specific yield of an aquifer is defined as the ratio of: (1) the volume of water drained from an aquifer by gravity, for a unit value of head decline, to (2) the volume of the aquifer. In other words, if a cubic foot of aquifer material yields 0.1 cubic foot of water when the level of saturation drops 1 foot, its specific yield would be 0.1. The normal range for most aquifer materials is from about 0.01 for clay to about 0.3 for clean sand and gravel (Freeze and Cherry, 1979, p. 61).

The same definition for specific yield applies to confined aquifers; however, if the head decline does not desaturate the aquifer, the term is referred to as specific storage. The water released comes from compression of the aquifer material and expansion of the interstitial water due to the decline in pressure head; thus, a much smaller volume of water is released. When specific storage is multiplied by the aquifer thickness, the storage coefficient (storativity) of the aquifer is obtained. The storativity of a confined aquifer commonly ranges from 5×10^{-3} to 5×10^{-5} (Freeze and Cherry, 1979, p. 60).

Methods of Hydrologic Data Collection

A network of 68 water-table wells 20 to 500 feet deep and 9 wells 60 to 400 feet deep that penetrate confined aquifers (plate 1) was used to observe seasonal water-level fluctuations. Fifteen of these wells were installed by the U.S. Geological Survey from 1980 to 1982 and the others were existing privately owned wells. The water levels were measured monthly from March 1981 to December 1982 and quarterly thereafter until October 1983. Water levels were referenced to land-surface altitude, which was estimated from a topographic map of the the valley having a 1:4,800 scale with a 5-foot contour interval (Genge Aerial Surveys, 1977). This allowed estimation of water-level altitudes to within ±2.5 feet. The measurements have been published in U.S. Geological Survey data reports (1981, p. 386-390; 1982, p. 344-348; 1983, p. 306-314; 1984, p. 230-232).

Most wells in the network that penetrate confined aquifers are old stockwater wells, many in operation since the early 1900's. These wells were used because they were easily sealed off for a head measurement, whereas many newer wells have pumps installed, making measurement difficult. Also, newer wells are commonly perforated throughout their entire depth, or in several zones, giving a head value representative of more than one discrete depth interval. Discussions with valley residents indicate that the older wells consist of open-ended casing perforated only near the bottom and emplaced by hydraulic jetting, which gives a more accurate head value for a specific depth than does the composite head obtained from newer wells.

Streamflow has been measured continuously since about 1940 at gages on the East Fork Carson River near Gardnerville, the West Fork Carson River at Woodfords, and the Carson River near Carson City (U.S. Geological Survey, 1983, p. 116, 120, 123). Other gages on Daggett, Pine Nut, and Buckeye Creeks have been in operation for 4 to 20 years.

Previous estimates of runoff from tributary streams along the Carson Range have been made with only minimal streamflow measurements. To accurately estimate surface-water runoff, streamflow measurements at 15 perennial streams and springs on the west side of the valley (plate 2) were made at roughly monthly intervals from May 1981 to October 1983. Measurements made for this study are published by the U.S. Geological Survey (1981, p. 356-357; 1982, p. 313-314; 1983, p. 275-276).

The Federal Watermaster's Office began to record diversion flows on major ditches in 1982. These records and estimates of average diversion flows were obtained from Garry Stone of the Federal Watermaster's Office (oral communication, 1984).

GEOLOGIC SETTING

Geologic History

Approximately 100 million years ago (Cretaceous age), the molten granitic magma of the Sierra Nevada pluton was intruded into sedimentary and volcanic rocks of Triassic and Jurassic age (140 to 240 million years old). Uplift associated with this intrusion was followed by a long period of erosion, producing an area of low relief by Oligocene time (30 million years ago; Stewart, 1980, p. 110). Basin-and-Range faulting, which produced the present topography, began about 17 million years ago (Stewart, 1980, p. 110); and deposition of Tertiary sediments onto the eroded bedrock surface began after that time, from 15 to 5 million years ago. Continued faulting tilted the Tertiary sediments toward the west, and deepened the Carson Valley basin, where unconsolidated basin-fill deposits were deposited from Quaternary (Pleistocene) time (about 2 million years ago) to the present day.

Structural Features

Carson Valley lies at the extreme western margin of the Basin and Range province, and is bounded by the Sierra Nevada province on the west. It is a typical Basin and Range valley; its long axis is oriented north-south, with a down-dropped structural block beneath the valley floor and upthrown blocks to the east and west.

The mountain blocks bounding the valley are west-tilted structural units (Stewart, 1980, p. 113), with Carson Valley occupying the down-faulted western edge of the Pine Nut block (Moore, 1969, p. 18). A steep, well-defined normal fault creates the 5,000-foot high escarpment of the Carson Range on the west, whereas a diffuse fault zone, up to 6 miles wide, underlies the east side of the valley, dividing the Pine Nut block into several smaller blocks (see plate 2). Continued westward tilting of the Pine Nut block is shown by recent faulting (200-1,000 years old) along the east scarp of the Carson Range (Pease, 1980, p. 15) and by displacement of the Carson River to the extreme west side of the valley (Moore, 1969, p. 18).

Gravity data gathered and interpreted for this study (Maurer, 1984) show the depth to bedrock and, thus, the thickness of basin fill in the study area (plate 2). The most conspicuous feature is an elongated basin beneath the western half of Carson Valley that is about 5,000 feet deep at a point 2 miles southeast of Walleys Hot Springs. North of this basin, a bedrock high extends to the northeast from under Hobo Hot Springs to just south of Stewart. Northwest of this ridge, a subbasin has formed beneath Jacks Valley that is as much as 1,400 feet deep. The steep gradient on the east side of the main basin implies offset of the basement along a north-south line from the west margin of Hot Springs Mountain to the Minden-Gardnerville area, with about 2,000 feet of relief. East of this feature, the valley fill averages about 800 to 1,000 feet in thickness, with isolated subbasins reaching 1,500 to 2,500 feet in thickness.

The configuration of the bedrock surface beneath Carson Valley indicates that the Pine Nut block is composed of at least two, and probably several, smaller structural blocks.

As described previously, the area has been actively faulted for the past 17-20 million years, and Carson Valley has probably received sediment eroded from the Carson Range and deposited by the Carson River and other tributaries throughout most of the Pleistocene. Total structural offset of the granitic basement is at least 5,000 feet and possibly as much as 10,000 feet (see plate 2 and figure 10).

Lithologic Units

The Carson and Pine Nut Ranges are composed mainly of granitic rocks about 100 million years old (Cretaceous age) that probably form the bedrock beneath the floor of Carson Valley (Pease, 1980, p. 2; Moore, 1969, p. 18). Metavolcanic and metasedimentary rocks of Triassic to Jurassic age (140 to 240 million years old) are also present as roof pendants in the granitic intrusions in both the Carson and Pine Nut ranges (Armin and others, 1983; Stewart and Noble, 1979). Stewart and Noble also mapped an exposure of Triassic carbonate rocks forming the ridge due east of Fish Spring Flat.

Low on the western flanks of the Pine Nut Range and at other isolated outcrops (plate 2), lake and stream deposits less than 25 million years old (Tertiary age) dip westward beneath the younger fill of Carson Valley (Moore, 1969, p. 19). These deposits differ from place to place in their degree of compaction (Pease, 1980, p. 14); they are described as soft sediments by Moore (1969, p. 19), whereas Stewart and Noble (1979) describe them as shales, siltstones, and sandstones. They are predominently fine grained and similar in composition to the Truckee Formation of Miocene and

Pliocene age near Virginia City (Moore, 1969, p. 13). Moore (p. 19) suggests a total thickness of several hundred feet for the Tertiary sediments, whereas Pease (1980, p. 4) mapped a 600-foot section exposed near Jacks Valley. Gravity data (Maurer, 1984) suggest a thickness of over 1,000 feet on the extreme east side of the valley.

Drillers' logs suggest that the Tertiary sediments are probably downfaulted to considerable depth except in the Indian Hills and Jacks Valley areas. Outcrop relationships seen in the Jacks Valley area, Johnson Lane area, and eastern parts of the basin suggest that Tertiary sediments form the basal unit overlying the granitic bedrock throughout much of the basin.

Unconsolidated sedimentary units up to 2 million years old (Quaternary age) vary in lithology from fine-grained flood-plain deposits of the Carson River to coarse, boulder-rich alluvial-fan deposits flanking the Carson Range. The flood-plain deposits consist of generally clean, well-sorted, medium to fine sand and silt with occasional gravel and clay lenses. They become coarser and more boulder-rich to the south, where the East and West Forks of the Carson River enter the valley, and finer toward the north end of the valley.

The alluvial-fan deposits flanking the west side of the valley and the fluvial deposits of the Carson River probably differ greatly in their lithology. The steep mountain drainages provide boulder-rich, coarse material, much of which was probably a component of very poorly sorted debris flows. This contrasts greatly with the well-sorted sand and silt of the Carson River flood plain. Intertonguing of the two deposit types occurred as the valley floor was downfaulted (see figure 10). The east side of the valley lacks well-defined alluvial fans except along the flanks of Hot Springs Mountain near Johnson Lane. Near land surface, fine-grained sediments eroded from the Tertiary formations are mixed with relatively coarse-grained stream deposits of Buckeye and Pine Nut Creeks, and they intertongue with Carson River flood-plain deposits about 2 miles east of the Douglas County Airport.

Because of the considerable depth of Carson Valley and the lack of existing wells pentrating over 1,000 feet, the thickness or the presence of the Tertiary sediments and degree of consolidation and grain-size of Quaternary sediments are unknown for a large volume of the basin-fill reservoir. The effect of these uncertainties on the ground-water model is discussed in the section on model sensitivity.

STREAMFLOW

Streamflow enters the valley from the south by way of the East and West Forks of the Carson River, at a rate that averages about 360,000 acre-ft/yr. The Carson Range on the west side of the valley has several perennial streams that reach the valley floor by way of steeply sloping alluvial fans. The Pine Nut Range produces two perennial streams, Pine Nut and Buckeye Creeks; however, flow from these streams rarely reaches the valley floor. Where streamflow reaches the valley floor, it is diverted into a complicated flow-routing system for irrigation that uses the natural stream channels, along with hundreds of ditches, to distribute the streamflow over the valley floor. The water table is less than 5 feet deep over much of the valley floor, allowing close contact between surface water and ground water throughout the valley. Surface-water outflow, measured in the bedrock narrows of the Carson River near Carson City, averages about 291,000 acre-ft/yr and represents virtually the total outflow from Carson Valley.

Streamflow in the Valley

Ground-water and surface-water levels were measured near streams and ditches to identify gaining and losing reaches of the surface-water system. Where depth to water is shallow, irrigation ditches with beds below the water table incur seepage from the aquifer, with the ditch system forming a drain. Where the water table is deeper than the bed of the stream or ditch, flow is lost to the aquifer by infiltration. Generally, streams and ditches west of U.S. Highway 395 on the valley floor gain flow, draining the water table, whereas streams and ditches east of U.S. Highway 395 and on the margins of the valley floor west of Highway 395, where depth to water is greater, lose flow. Measurement of the water-table gradient near ditches, which began in 1982, showed that during the wet years of 1982 and 1983, the direction of flow between the ditch and the water table for a given site did not change seasonally. This was not true for measurements made in 1985, a dry year. Water-table altitudes dropped during 1985, and many reaches that were gaining during the wet years began losing flow to the aquifer.

Streamflow from the Mountain Block

To more accurately estimate the runoff from mountain drainages having perennial streams, streamflow measurements were made, usually at monthly intervals, at the contact between bedrock and basin fill in each drainage. Snow and icing conditions often made winter measurements difficult and inaccurate. The numerous small springs, seeps, and streams in the Jacks Valley area were not measured monthly because their flow is largely ephemeral in most years.

Daggett Creek is the only perennial stream draining the Carson Range that has a long-term streamflow record. This station was used as an index gage for correlation of monthly measurements at seven other sites to obtain long-term estimates of runoff. For Fredricksburg, Luther, Mott, and Monument Creeks, linear regressions of instantaneous measurements at each site provided acceptable relations with average daily flows recorded at Daggett Creek; correlation coefficients[1] ranged from 0.88 to 0.98 (table 1). Measurements at Jobs, Genoa, and Sierra Creeks, however,

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[1] Generally, correlation is weak when the coefficient is less than 0.50 and strong when the correlation is greater than 0.80 (Devore, 1982, p. 449).

had correlation coefficients of less than 0.50. To smooth errors in measurement and variations in runoff between individual drainages, the cumulative flow at all seven miscellaneous-measurement sites was plotted against the daily flow at Daggett Creek, and a good fit was obtained. Cumulative flow was then plotted against individual flow measurements at Jobs, Genoa, and Sierra Creeks. Correlation coefficients of 0.87 and 0.92 were obtained for Genoa and Sierra Creeks. In contrast, Jobs Creek still had a correlation coefficient of less than 0.50. Winter measurements at Jobs Creek are assumed to have been inaccurate. Using only spring-through-fall measurements at Jobs Creek and plotting wet and dry years separately resulted in good linear relationships with Daggett Creek flow, with correlation coefficients of 0.98 and 0.99, respectively. The relationships obtained for spring-to-fall months at Jobs Creek are assumed also to be adequate for winter months. Using these relationships and the 18-year record at Daggett Creek, estimates of mean monthly and annual flows were obtained for each of the other seven streams, and are listed in table 2.

TABLE 1.—*Correlation between flow of perennial streams and flow of Daggett Creek for period May 1981–October 1983*

Stream	Mathematical relation[1]	Correlation coefficient
Fredricksburg Creek	$y = 1.03 + 2.44(x)$	0.90
Luther Creek	$y = -1.08 + 3.14(x)$	.88
Monument Creek	$y = 1.44 + 0.85(x)$	.98
Mott Creek	$y = 0.82 + 1.27(x)$	.96
Jobs Creek (dry year)	$y = 1.10 + 0.40(x)$	.99
Jobs Creek (wet year)	$y = 0.97 + 0.42(x)$	.98
Cumulative flow[2]	$y = 3.11 + 9.02(x)$	.97
Sierra Creek vs. cumulative flow	$y = -1.08 + 0.15(x)$	.92
Genoa Creek vs. cumulative flow	$y = -0.16 + 0.05(x)$	.87

[1] Symbols: x, flow of Daggett Creek; y, flow of listed stream.

[2] Cumulative flow of all listed streams, excluding Daggett Creek.

TABLE 2.--*Estimated long-term runoff and precipitation for perennial stream drainages*

Stream number (plate 2)	Creek name	Drainage-basin area (acres)	Total precipitation (acre-feet per year)	Estimated runoff	
				Acre-feet per year[1]	Percent of total precipitation
4	Daggett Creek	2,410	6,300	1,400	22
6	Fredricksburg Creek	2,210	6,400	4,700	73
7	Luther Creek	2,840	7,600	2,800	37
8	Jobs Creek	1,890	5,600	1,800	32
9	Stutler Creek	1,220	3,500	1,200	34
10	Monument Creek	1,480	3,800	2,300	60
11	Mott Creek	1,290	3,200	2,300	72
12	Genoa Creek	1,510	3,600	900	25
13	Sierra Creek	2,000	4,900	1,000	20
Total		16,850	44,900	18,400	41

[1] Based on records of streamflow for Daggett Creek, water years 1964-83, and equations in table 1.

Diversions from Stutler Creek above the point of measurement made correlation of that flow impossible. Estimated flow at Stutler Creek, which is listed in table 2, represents an average of estimated diversions and flows measured in water years 1981-83. (A water year begins in October, ends in September, and is designated by the calendar year in which it ends.) The relationships listed in table 2 are based on a large range in runoff variation but only 3 years of data, and should be considered preliminary until substantiated by continued data collection.

The flow at several springs along the Carson Range also was measured (see plate 2). No correlation of springflows with the flow of Daggett Creek was possible. Estimated springflows, listed in table 3, represent the average of flows measured in water years 1981-83. In comparing springflow to flow in perennial streams, peak flows at springs were attained toward the end of summer, usually in August, whereas perennial streams peaked in May or June in response to snowmelt runoff. This implies that snowmelt recharge to the spring systems is attenuated by the slow groundwater flow through subsurface fractures or weathered zones in the granitic bedrock of the Carson Range.

TABLE 3.--*Estimated discharge of principal springs on west side of valley*

Spring number (plate 2)	Name	Acre-feet per year[1]
14	Benson (south orifice)	1,200
15	Benson (north orifice)	1,200
16	Miller	700
17	Barber	500
19	Sheridan	900
--	Walleys[2]	700
Total		5,200

[1] Average of flows measured in 1981-83 water years, except as indicated.
[2] Nevada State Engineer's Office, written communication, 1970.

GROUND WATER

Geohydrologic Units

For this report, the Carson Valley ground-water basin was divided into three geologic units having different hydrologic characteristics. The first and most important unit contains the Quaternary unconsolidated sedimentary deposits, and is composed of three subunits: (1) alluvial-fan deposits along the western side of the valley, (2) an unconfined (water-table) subunit, and (3) a confined subunit that does not have well-defined boundaries and is in hydraulic connection with the first two subunits. The second major unit is composed of the Tertiary sediments (see section titled "Lithologic Units"). This unit is exposed on the east side of the valley and probably is present at depth throughout the remainder of the valley. The third unit is the granitic and metamorphic bedrock surrounding and underlying the basin-fill deposits.

The first two units constitute what will be referred to as the basin-fill reservoir in this report. The area of the basin-fill reservoir used in this report is shown on plates 1 and 2. The boundary as drawn excludes an area of relatively thick Tertiary sediments north of Fish Springs Flat (plate 2). This area is separated from the main part of the valley by a ridge of relatively shallow bedrock that extends southeast from Hot Spring Mountain. Consequently, it was not considered as part of the basin-fill reservoir in Carson Valley.

Occurrence and Movement of Ground Water

Quaternary Unconsolidated Units

Both unconfined and confined aquifers have been noted in Carson Valley by previous workers (Walters, Ball, Hibdon & Shaw, 1970, p. 16; Spane, 1977, p. 139). Lithologic cross sections using 245 drillers' logs were prepared by Dillingham (1980, p. 40) to determine whether a continuous confining bed existed across the valley; he concluded that a single valley-wide confining bed does not exist. Logs from several wells on the valley floor, however, show clay layers 30 to 40 feet thick at altitudes ranging from 4,520 feet south of Gardnerville to 4,480 feet near Johnson Lane. These altitudes correspond to the depths where many wells develop artesian flow--200 to 300 feet below land surface. The apparent lack of continuity in these clays suggests that they were deposited as discontinuous lenses.

Wells that penetrate confined aquifers are found at shallower depths on the west edge of the valley than toward the center of the valley. Here, confined heads may result where wells penetrate finer flood-plain deposits overlying the coarse materials in sloping channels of buried alluvial fans.

As discussed later, two confined aquifer systems probably exist in the Quaternary unconsolidated hydrologic unit: one along the extreme west margin of the valley floor associated with the alluvial fans of the Carson Range, and another beneath the central part of the valley floor.

Figure 3A shows water-table contours, which are generally parallel to land-surface contours. Ground water characteristically flows from the east and west, toward the center of the valley, and then north along an axis about 2 miles west of U.S. Highway 395. Along the main axis of the valley, water-level gradients range from about 100 ft/mi in the southwest to as low as 5 ft/mi in the north. On the east side of the valley, ground-water flow is to the west, with gradients from 20 to 100 ft/mi. Beneath the alluvial fans on the west side of the valley, ground water moves generally west to east, with gradients as great as 100 ft/mi. In the Jacks Valley area (the northwest corner of Carson Valley), ground-water flow is to the southeast, with a gradient exceeding 100 ft/mi.

Confined water levels range from 5 to 20 feet above land surface on the valley floor. A contour map of confined heads (figure 3B) shows the same general configuration as for the unconfined water levels, but with reduced gradients. This suggests similar flow directions in both aquifers, and hydraulic connection between the two.

Also shown in figure 3B are areas with slight artesian pressures at shallow depths (reported by the U.S. Bureau of Reclamation, 1961, plate 5). The two areas adjacent to the alluvial fans on the west side of the valley could be due to upward leakage of water that has been recharged through the alluvial fans into the fluvial sediments of the Carson River flood plain. The northern shallow artesian area could be due to upward leakage of deeper water caused by the lack of a confining layer in this area (see figure 10).

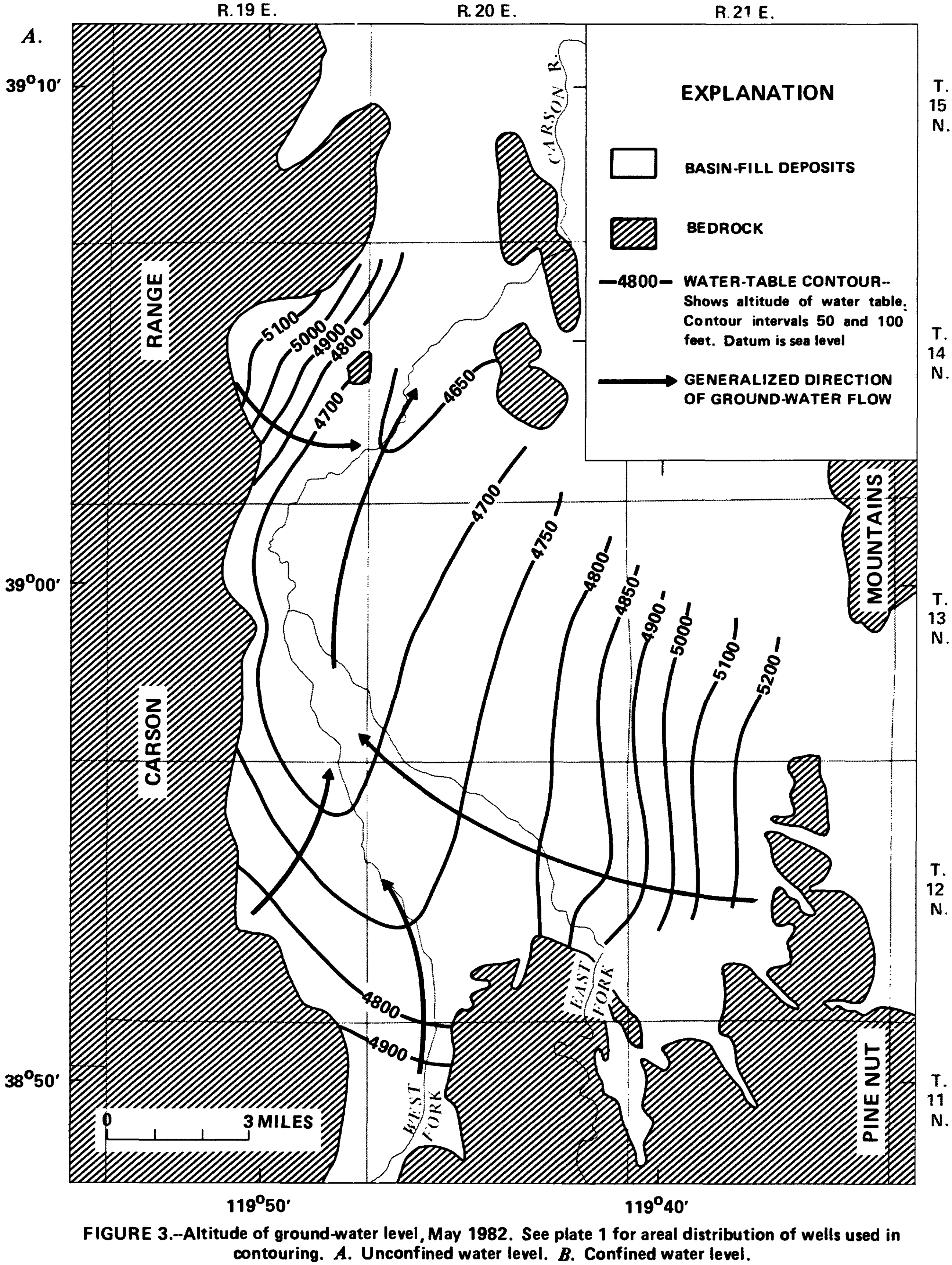


FIGURE 3.--Altitude of ground-water level, May 1982. See plate 1 for areal distribution of wells used in contouring. *A*. Unconfined water level. *B*. Confined water level.

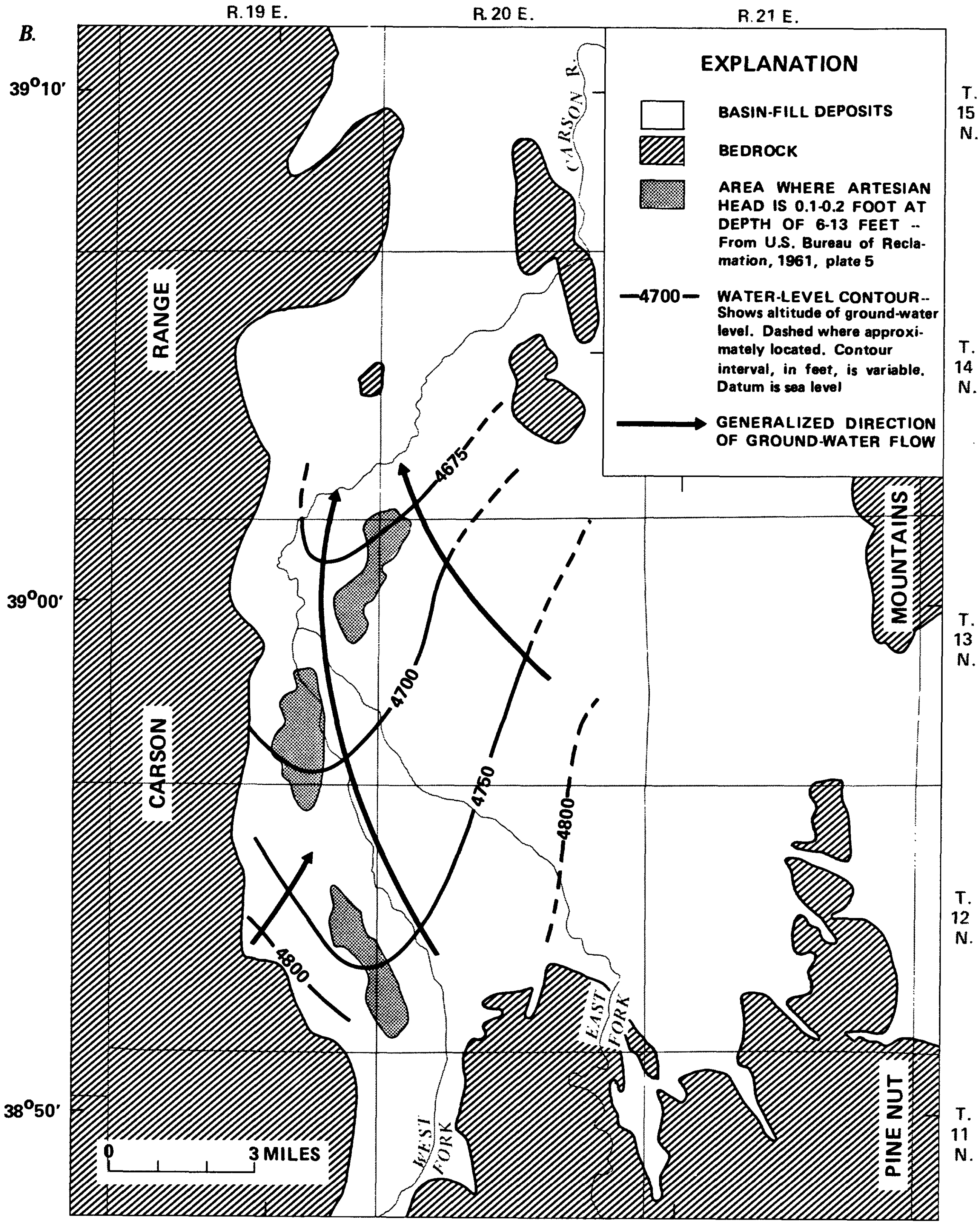


FIGURE 3.--Continued.

Specific-yield maps (Dillingham, 1980, plates 2 to 8) show that only very coarse sediments occur in that area to a depth of 400 feet. Thus, upward gradients in this area probably exist through the entire sedimentary column to a depth of at least 400 feet.

As shown in figure 4, the depth to water increases from about 5 feet on the valley floor to more than 100 feet on the fans along the margins of the valley.

Tertiary Sediments

Logs of wells on the east side of the valley show clay units 40 to 80 feet thick separated by 10- to 20-foot sand and gravel beds. The static water level lies 10 to 50 feet above the depth where water was first observed during the drilling. At most wells, that water-bearing unit was a sand or gravel bed. Thus, the clay units probably constitute confining beds, with water moving mainly through the sand and gravel.

Water-level contours in figure 3A show a change in gradient from about 20 ft/mi to more than 100 ft/mi along the diffuse fault zone on the east side of the valley. Tertiary sediments constitute the major aquifer east of the fault zone, and the steep gradient can be partly attributed to the lower hydraulic conductivity of the unit. Also, faulting may offset water-bearing beds within the Tertiary sediments, impeding lateral ground-water flow and increasing the east-to-west gradient.

Exactly how water moves through the Tertiary sediments and enters the Quaternary unconsolidated units is not known, but the zone of faulting on the east side of the valley probably down-drops the Tertiary sediments to a considerable depth, allowing westward flow from water-bearing units in the Tertiary sediments to the Quaternary unconsolidated aquifers (see figure 10).

Bedrock

Near Genoa, most wells drilled 100 to 300 feet into bedrock have confined heads, according to Dillingham (1980, p. 41). This suggests that fairly deep weathered or fractured zones exist in the bedrock, providing a subsurface avenue of recharge from the mountain blocks to the basin-fill deposits. This zone also sustains perennial stream and spring flow in the mountain block along the west side of the valley. Below this zone, the bedrock unit is assumed to have a very low hydraulic conductivity, making it an aquifer of little significance to the area.

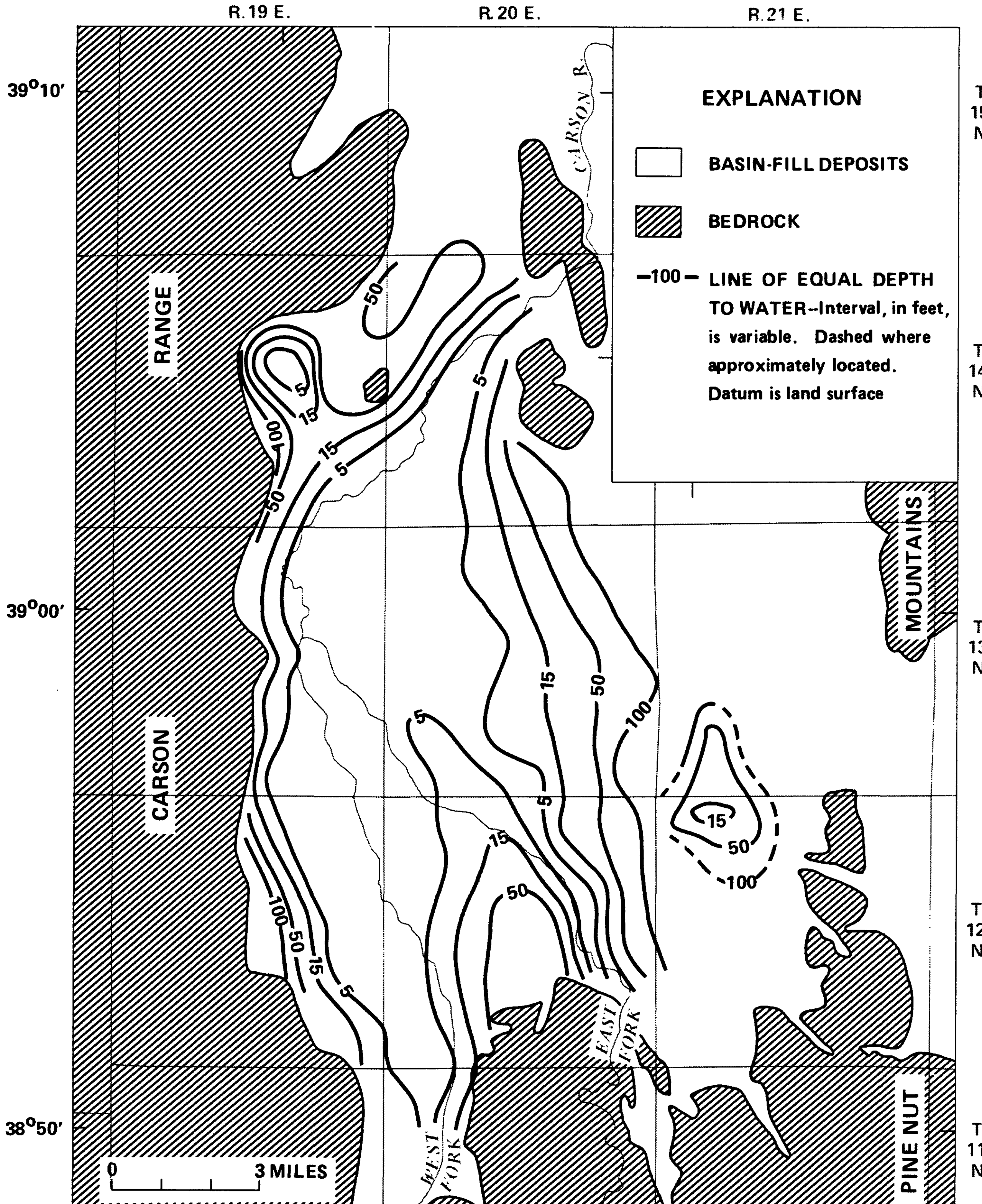


FIGURE 4.--Approximate depth to ground water, 1982.

Water-Level Fluctuations

In December 1981, hydraulic heads of 15 wells that the U.S. Bureau of Reclamation had measured in December 1956 were remeasured, and no significant net change in water level or artesian head was seen for the 25-year period. The 1956 and 1981 water years both had below normal precipitation, with only 6.52 and 6.35 inches of precipitation, respectively, measured at Minden (long-term average, 8.51 inches). No estimates of ground-water pumpage exist for 1956; however, the population of the entire valley was only about 2,500 (Douglas County Planning Commission, oral communication, 1986), compared to about 25,000 in the 1980's, and few of the irrigation wells presently in use existed in 1956. Thus, pumpage in 1956 was probably an order of magnitude less than the estimated 14,500 acre-feet in 1981. This implies that ground-water withdrawals as of 1981 had not yet caused a change in ground-water storage.

Figures 5A and B show examples of hydrographs of water-table wells on the valley floor (table 4 lists information for the wells in figure 5). Monthly water-level measurements indicate seasonal fluctuations of 5 to 10 feet, with most levels reaching an annual peak during spring runoff in May. Water levels are lowest (deepest) in the fall over most of the valley floor, except at wells 9 and 15 on the east side of the valley where the lowest levels preceded the spring peak. Spring runoff begins when warm temperatures melt the winter snow pack; this is often a dramatic event in the valley, with large areas inundated by flood water. In dry years, irrigation commonly begins before the subdued spring runoff, as ranchers use the surface water while it is available. When this happens, percolation to the shallow water table aids in producing the spring hydrograph peak, even when the spring runoff is only moderate.

Streamflow decreases after the spring runoff, and the stress of evapotranspiration increases. This causes lowering of the water table at the end of the summer, even during years of abundant surface-water supplies such as 1982 and 1983. Wells on the west side of the valley floor begin recovery almost immediately after the stress of evapotranspiration ceases in the fall. Wells along the east side of the valley floor do not recover until the following spring runoff (see wells 9 and 15, figure 5B). The same difference in recovery times between wells on the east and west sides of the valley during the early 1950's is reported by the U.S. Bureau of Reclamation (1954, p. 18). The difference suggests that upward leakage from confined aquifers underlying the valley floor and from the alluvial-fan deposits on the western side of the valley causes the relatively quick recoveries there, compared to those for wells on the east side.

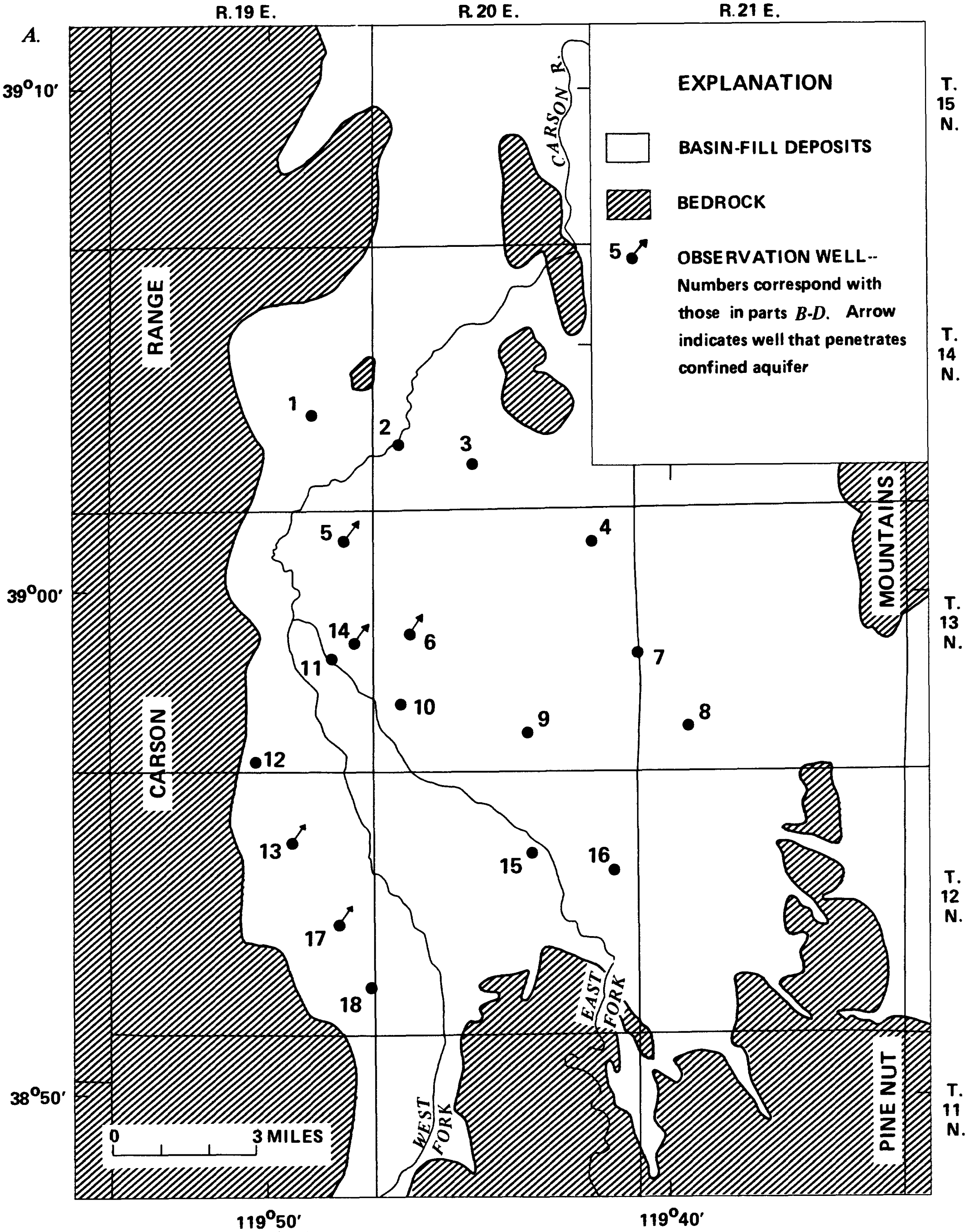
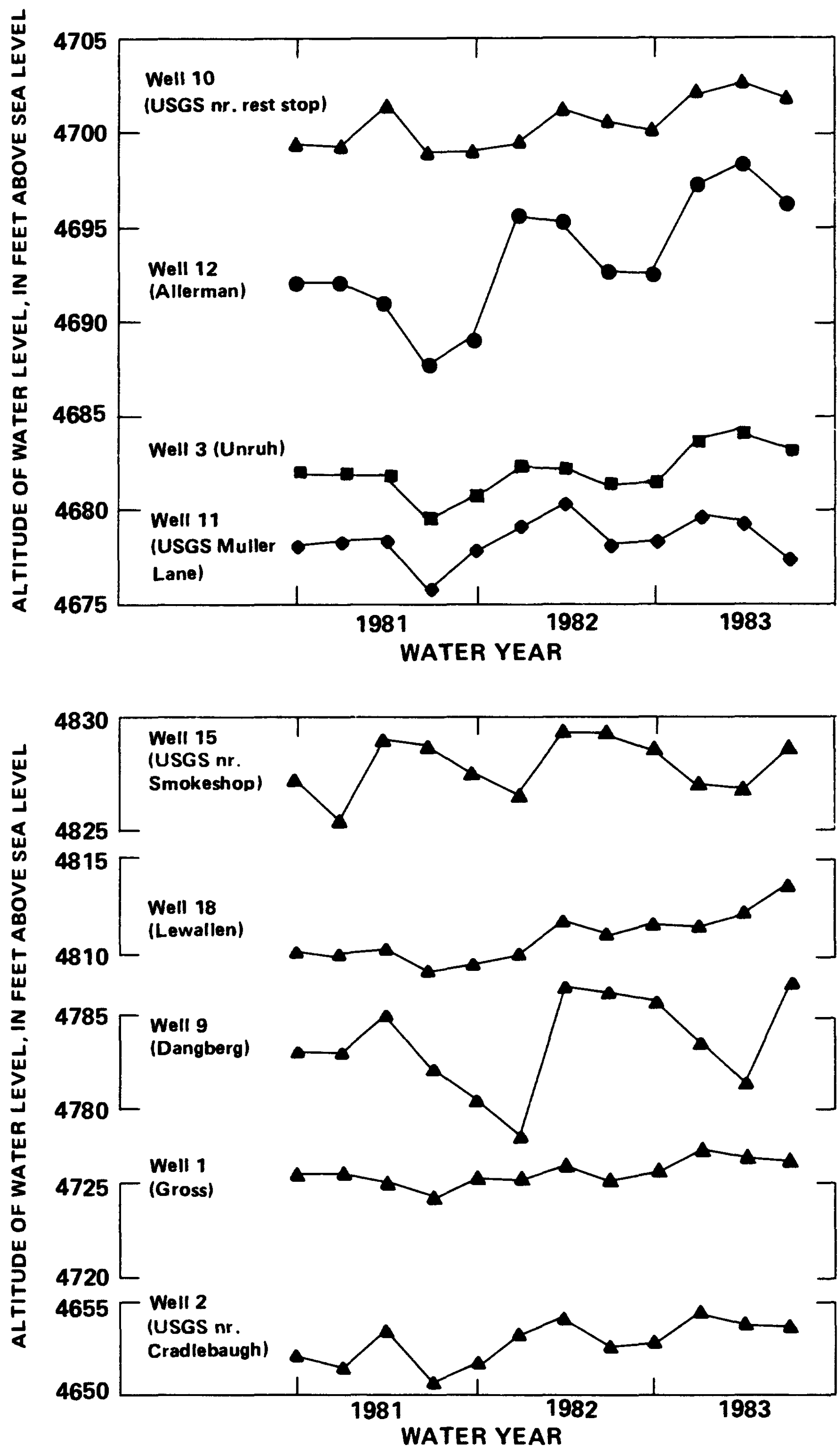
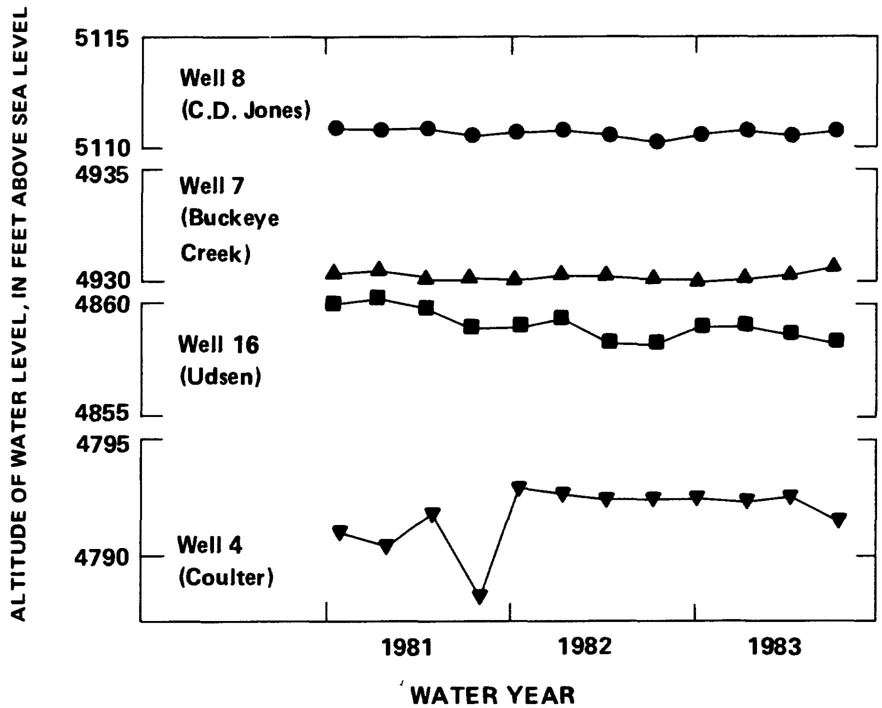


FIGURE 5.--Water-level fluctuations in selected wells, 1981-83. *A*. Observation wells (table 4). *B-D*. Hydrographs for *(B)* wells on valley floor, *(C)* wells on east side of valley, and *(D)* artesian wells.

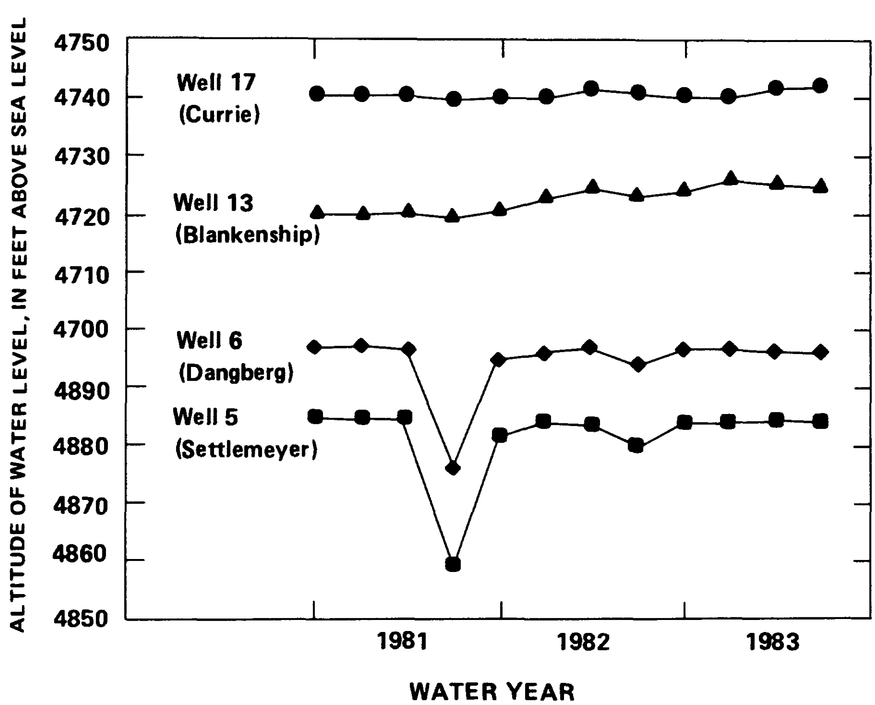


B. Wells on valley floor

FIGURE 5.--Continued.



C. Wells on east side of valley.



D. Artesian wells on west side of valley (Nos. 13 and 17) and in center of valley (5 and 6).

FIGURE 5.--Continued.

TABLE 4.--*Principal observation wells*

["--" indicates data not available]

Well number (fig. 2)	Name	Location[1]	Depth below land surface (feet) Total	Perforated interval	Diameter (inches)	Water level: confined (C), or water table (W)
1	Gross	T14N R19E 26ABBC	--	--	8	W
2	USGS near Cradlebaugh	T14N R20E 30DCCB	20	10-20	2	W
3	Unruh	T14N R20E 33BCDA	210	60-210	13	W
4	Coulter	T13N R20E 12BCAD	300	256-276	8	W
5	Settlemeyer	T13N R19E 12BBAD	400	--	3	C
6	Dangberg	T13N R20E 19AAAB	318	--	3	C
7	Buckeye Creek	T13N R21E 19CBBA	140	--	6	W
8	C. D. Jones	T13N R21E 32BDAD	608	50-196	14	W
9	Dangberg	T13N R20E 22CADD	--	--	14	W
10	USGS near Rest stop	T13N R20E 30DBBB	21	18-21	2	W
11	USGS Muller Lane	T13N R19E 23DDAD	21	18-21	2	W
12	Allerman	T13N R19E 33DADD	80	--	8	W
13	Blankenship	T12N R19E 11CDCC	60	--	4	C
13A	Dangberg	T13N R19E 24CADD	401	--	3	C
14	USGS near Smokeshop	T12N R20E 14BABC	21	11-21	2	W
15	Udsen	T12N R20E 13DDBB	250	230-250	6	W
17	Carrie	T12N R19E 24CCAA	82	66-82	8	C
18	Lewallen	T12N R19E 36ADDA	198	108-198	12	W

[1] First unit: township. Second unit: range. Third unit: section number and letters designating the quarter section, quarter-quarter section, and so on (A, B, C, and D indicate the northeast, northwest, southwest, and southeast quarters, respectively). Thus, "12BCAD" indicates the SE¼ (D) of the NE¼ (A) of the SW¼ (C) of the NW¼ (B) of section 12.

In contrast to the seasonal fluctuations of ground-water levels in the alluvial-fan deposits in the western part of the valley and on the valley floor, water levels change little if at all seasonally on the easternmost side of the valley (figure 5C). Wells on the east side also show little response to changes in annual precipitation. The lack of water-level fluctuations on the east side is probably due partly to the lack of seasonally varying recharge and discharge stresses, such as the flood irrigation and evapotranspiration on the valley floor. Also, the less permeable Tertiary sediments could have a dampening effect on seasonal recharge from the Pine Nut Range, 3 to 4 miles farther to the east, and probably prevent significant recharge from precipitation.

Hydrographs of wells that penetrate the confined aquifer on the extreme west side of the valley floor differ from those in the center of the valley (see figure 5D). Wells 5 and 6 near the center of the valley show large declines of 20 to 25 feet in the fall of dry water year 1981, caused partly by agricultural pumping and probably to a greater extent by a decrease in recharge to the confined aquifer. Only minor declines were observed in the fall of the wet water years, 1982 and 1983. In 1981, artesian flow stopped and water levels approached those measured in nearby unconfined wells. Recovery in the next quarter, however, was rapid. During 1981-83, wells 13 and 17 near the west side of the valley showed virtually no response to pumping and had a slight spring peak. As stated previously, these wells probably tap alluvial-fan deposits that receive recharge from the adjacent mountain basins. These two confined systems probably merge less than a mile east of the eastern edge of the alluvial fans.

Aquifer Properties

Drillers' logs of 245 deep wells in Carson Valley were evaluated and used to develop maps of specific yield for the uppermost 300 feet of valley fill at 20- to 100-foot intervals (Dillingham, 1980, plates 2 to 8). Figure 6 shows the estimated distribution of average specific yield for the upper 300 feet of basin-fill deposits in Carson Valley. Specific-yields are high--20 percent in the west-central part of the valley floor. Values decrease toward the east, where the fine-grained Tertiary sediments are a major component of the valley fill. Even farther to the east, where the Tertiary sediments are exposed, the estimated specific yield is only about 5 percent. A decrease is seen also on the west side of the valley, where the alluvial fans are poorly sorted, and at the north end of the valley floor, where flood-plain deposits of the Carson River are fine grained.

The percentages of coarse versus fine material listed in 263 drillers' logs in Carson Valley have been compiled by H. L. Dillingham (U.S. Bureau of Reclamation, written communication, 1983). During the present study, these percentages were used to calculate vertical and horizontal hydraulic conductivities (K_h and K_v, respectively) by using the following formulas (re-written from Freeze and Cherry, 1979, p. 34, eq. 2.32 and 2.31):

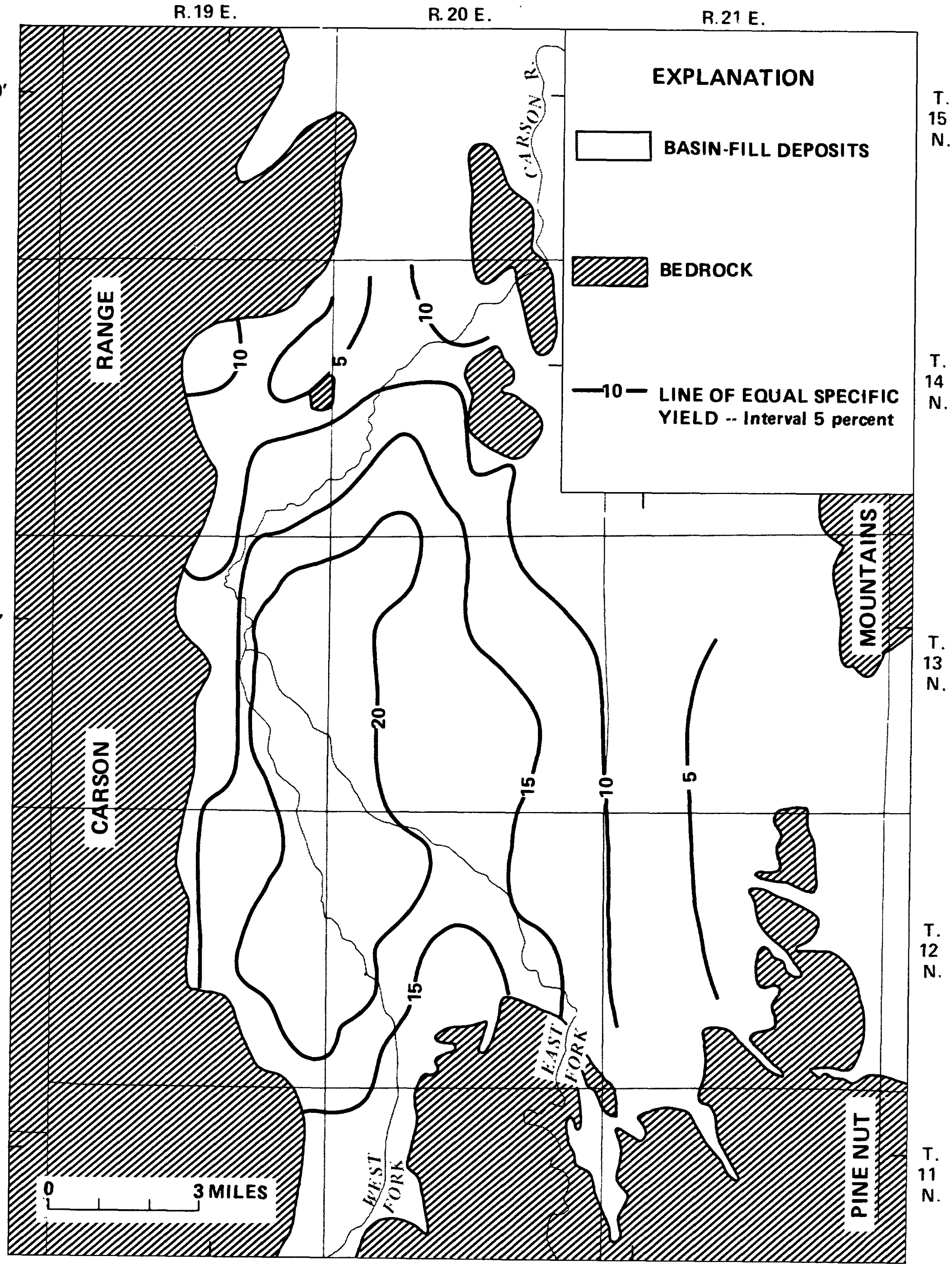


FIGURE 6.--Distribution of estimated average specific yield for upper 300 feet of basin-fill deposits.

$$K_h = (K_c)(\%_c) + (K_f)(\%_f) \text{ , and}$$

$$K_v = 1/(\%_c/K_c + \%_f/K_f) \text{ ,}$$

where K_c and K_f = hydraulic conductivities of coarse and fine sediments, respectively, and

$\%_c$ and $\%_f$ = proportions of coarse and fine sediments, respectively, expressed as decimal percent.

Using these equations, a computer program was developed to calculate horizontal and vertical conductivities from the coarse and fine percentages for all areas of the valley. These values were then used as initial conductivities for model calibration.

As a check on the distribution of horizontal conductivity obtained using the coarse-and-fine method, a formula developed by Theis (1963, p. 333) which uses drawdown, pumping time, and pumping rate to calculate transmissivity, was applied. Data from 150 drillers' logs from Carson Valley were considered adequate for application of the formula. The transmissivity thus obtained was then divided by the total perforated interval of each well to obtain an estimate of hydraulic conductivity.

On the valley floor, both methods produced similar values. On the east side of the valley, in Jacks Valley, and along the western alluvial fans, however, the Theis method indicated lower conductivities. H. L. Dillingham (U.S. Bureau of Reclamation, written communication, 1983) suggested that many of the drillers' log descriptions along the western alluvial fans and on the east side probably underestimate the amount of fine material encountered while drilling. Also, drillers do not note sorting of the sediments, which can skew the calculated percentages toward coarser material. Both of these factors would cause the coarse-and-fine method to overestimate conductivity. In these areas, the value calculated by the Theis formula appears to be a better approximation of the true conductivity.

Figure 7 shows the estimated distribution of horizontal conductivity for the upper 300 feet of valley fill. Values range from 10^{-3} to 10^{-4} ft/s on the valley floor and are as low as 10^{-5} ft/s for Tertiary sediments on the east side of the valley. Values calculated for wells 300 to 500 feet deep were generally much less than those for shallower wells, ranging from 10^{-5} to 10^{-6} ft/s. Data have been found for only one reliable pumping test in the valley, on the valley floor near the county airport. For this test, conductivity values ranged from 1.7×10^{-4} to 1.9×10^{-4} ft/s (U.S. Bureau of Reclamation, written communication, 1981).

Vertical conductivities estimated by the coarse-and-fine method for the upper 300 feet of valley fill were in the range of 10^{-8} to 10^{-10} ft/s. Figure 8 shows the distribution of estimated vertical conductivity for the valley. Areas of low vertical conductivity generally occur (1) where well logs indicate thick clay beds beneath the valley floor and (2) on the western alluvial fans.

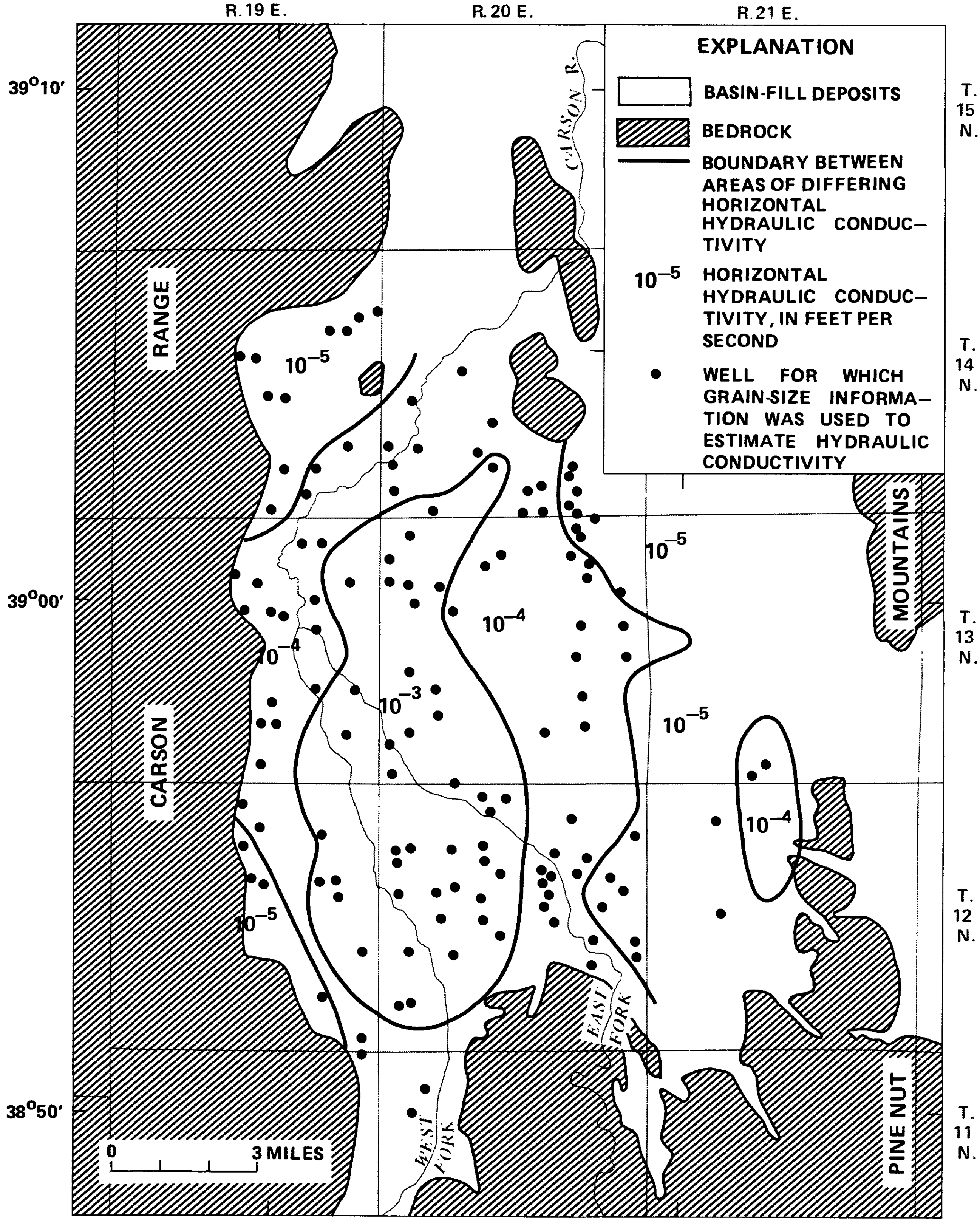


FIGURE 7.--Distribution of estimated average horizontal hydraulic conductivity for upper 300 feet of basin fill; based on relative proportions of coarse and fine sediments, and adjusted during model calibration.

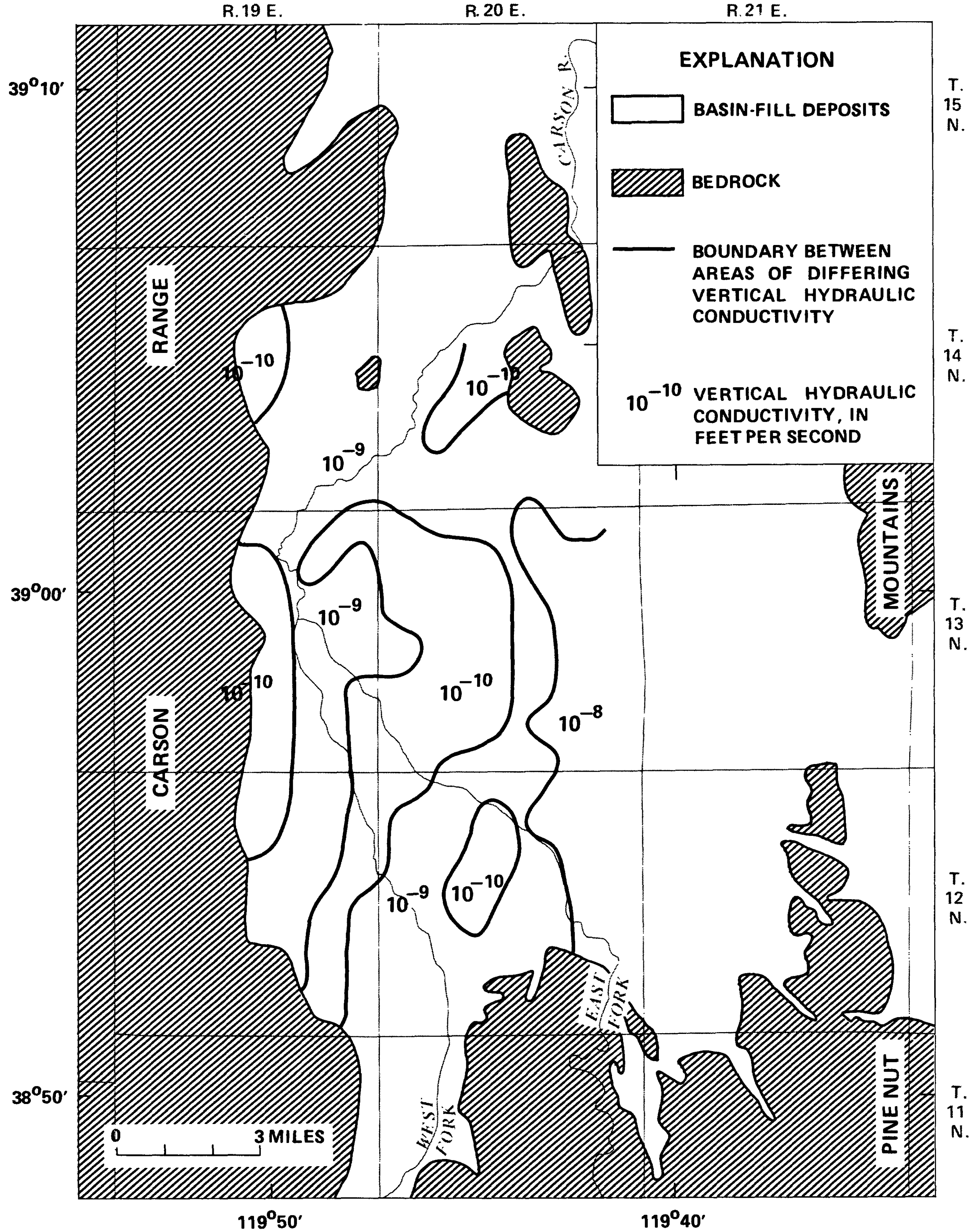


FIGURE 8.--Distribution of estimated average vertical hydraulic conductivity for upper 300 feet of basin fill, as adjusted during model calibration.

INFLOW TO AND OUTFLOW FROM THE BASIN-FILL RESERVOIR

The following sections discuss estimates of surface-water and ground-water inflow to and outflow from the basin-fill reservoir in Carson Valley, an area of about 94,000 acres (plate 1 and figure 1B). Except for surface-water flow of the East and West Forks of the Carson River, precipitation that falls on the Carson Valley drainage basin (plate 1 and figure 1B) is the ultimate source of all inflow to the basin-fill reservoir. The Carson Valley drainage basin includes the valley floor and drainage from areas that are tributary to the valley between the Woodfords and Gardnerville gages on the south and the Carson River gage on the north, excluding the Clear Creek drainage.

Components of inflow to the basin-fill reservoir include direct precipitation, surface-water flows of the East and West Forks of the Carson River, runoff from perennial and ephemeral streams, subsurface flow across the contact between bedrock and valley fill, and ground-water inflow from adjacent basins. Components of outflow from the reservoir include surface-water flow of the Carson River, evaporation from open-water bodies, and evapotranspiration from irrigated crops, native plants, and bare soil.

Long-term estimates of budget components must be considered approximations only, with surface-water inflow and outflow (Carson River) being the only components that have actually been measured over the long term. Even for these, estimates of long-term mean flow change with time. As an example, the long-term mean annual flow at the gage near Carson City, where continuous records have been collected for 44 years, increased by 19,500 acre-ft/yr, from 283,300 acre-ft/yr after the dry year of 1981 to 302,800 acre-ft/yr after the extremely wet years of 1982 and 1983 (U.S. Geological Survey, 1981, p. 151; 1983, p. 123). Evaporation and evapotranspiration have been measured only at selected sites in the basin, and these values were applied basin-wide. Precipitation also has been measured at only a few sites in the basin, and maps were developed from these data that estimate the distribution for the entire basin.

Inflow to and outflow from the water-table aquifer in irrigated agricultural areas are difficult to estimate, because ditches change from losing to gaining reaches and because the gradients driving flow between the surface-water and ground-water systems also change with time and location. These flow volumes are readily calculated by a calibrated ground-water model, and are discussed further in the numerical-model section.

Inflow

Precipitation

Plate 1 shows the distribution of precipitation in Carson Valley as derived by Spane (1977, p. 50-54), who used altitude, slope, exposure, and orientation at 329 points in the valley and correlated them with data from 43 long-term weather stations in western Nevada and eastern California to produce the distribution shown. Previous workers based their estimates on Hardman's (1965) precipitation map of Nevada, which considered only altitude and vegetation type in estimating the distribution of precipitation. Spane's version is considered, both by Dillingham (1980, p. 65) and herein, as the more accurate method in Carson Valley, and it therefore has been used for this study.

Volumes of annual precipitation were calculated by planimetering the areas between lines of equal precipitation on plate 1 and multiplying each area by the "midpoint" amount of precipitation. This resulted in an esti-mated average annual precipitation for the entire drainage basin of 350,000 acre-ft/yr. This is lower than the 387,000 acre-ft/yr calculated by Spane (1977, p. 54) and also lower than the value of 370,000 acre-ft/yr calculated by Glancy and Katzer (1975, table 17) because of the different areas considered in the three studies. Spane (1977) included the Clear Creek drainage at the north end of the basin, and the study area used by Glancy and Katzer included the area between the Markleeville and Gardnerville stream gages on the East Fork Carson River, for a total of 342,000 acres. In contrast, the area included in this study encompasses 284,000 acres, a difference of 58,000 acres. The 58,000-acre area receives more than 1 foot of precipitation per year, decreasing the 370,000-acre-ft/yr value for Glancy and Katzer's larger area to less than 312,000 acre-ft/yr for the smaller area considered in this study. Thus, the precipitation map developed by Spane (1977, plate 3) indicates significantly more precipitation for Carson Valley than was estimated by Glancy and Katzer.

The 94,000-acre surface of the basin-fill reservoir receives an estimated 70,000 acre-ft/yr of direct precipitation (table 6).

Potential Recharge from Precipitation

Potential recharge to the basin-fill reservoir in Carson Valley can be estimated using the general method described by Eakin and Maxey (1951, p. 79-81). The method assumes that for any given altitude zone, a particular percentage of the total precipitation constitutes potential recharge to the ground-water reservoir, with that percentage depending on the average amount of precipitation within the zone, as listed in table 5.

TABLE 5.--*Recharge percentages, by precipitation range, used in Eakin-Maxey method*[1]

Precipitation range (inches)	Potential recharge (percentage of total precipitation)
8-12	3
12-15	7
15-20	15
Over 20	25

[1] Eakin and Maxey (1951, p. 80).

Table 6 summarizes the potential ground-water recharge for the Carson Valley drainage basin using the Eakin-Maxey method. The term "potential recharge" is used because not all of the computed recharge reaches the basin-fill reservoir. For example, the shallow water table and the upward leakage of ground water adjacent to the Carson Range prevent appreciable recharge there, and much of the water thus is rejected as recharge; instead, it is evaporated, consumed by plants, or incorporated into the flow of the Carson River.

The estimated potential recharge in the Carson Valley basin is 49,000 acre-ft/yr (table 6). This computation differs from that made by Glancy and Kazter (1975, table 17) in that the precipitation amounts are based on (1) different drainage areas and (2) the distribution developed by Spane (1977).

The Eakin-Maxey method was developed for arid desert basins where most of the annual recharge is provided by precipitation in the surrounding mountains and supplied to the valley floor by runoff from ephemeral and perennial streams, with only a minor amount of precipitation falling on the valley floor itself.

TABLE 6.--*Estimated potential ground-water recharge for average long-term conditions, using Eakin-Maxey method*

Precipitation area[1] (acres)	Estimated annual precipitation: Range within area (inches)	Average (feet)	Total (acre-feet)	Estimated potential recharge: Percentage of total precipitation	Acre-feet per year
		EAST SIDE OF VALLEY			
770	>26	2.2	1,700	25	420
2,590	24-26	2.1	5,400	25	1,300
3,380	22-24	1.9	6,400	25	1,600
6,660	20-22	1.8	13,000	25	3,300
12,840	18-20	1.6	20,000	15	3,000
42,000	15-18	1.4	57,000	15	8,500
44,800	12-15	1.1	52,000	7	5,400
22,650	10-12	.9	21,000	3	630
8,090	8-10	.8	6,100	3	180
Total (rounded)	—	—	180,000	—	24,000
		WEST SIDE OF VALLEY			
2,780	>40	3.3	9,300	25	2,300
7,140	35-40	3.1	22,000	25	5,500
8,350	30-35	2.7	22,000	25	5,500
8,270	25-30	2.3	19,000	25	4,700
7,460	20-25	1.9	14,000	25	3,500
7,230	15-20	1.5	11,000	15	1,600
3,000	12-15	1.1	3,300	7	230
2,000	10-12	.9	1,800	3	50
Total (rounded)	—	—	100,000	—	23,000

TABLE 6.--*Estimated potential ground-water recharge for average long-term conditions, using Eakin-Maxey method*--Continued

Precipitation area[1] (acres)	Estimated annual precipitation: Range within area (inches)	Average (feet)	Total (acre-feet)	Estimated potential recharge: Percentage of total precipitation	Acre-feet per year
VALLEY FLOOR (BASIN-FILL RESERVOIR)					
93,540	8-10	0.8	70,000	3	2,100
ENTIRE VALLEY					
Grand total (rounded)	--	--	350,000	--	49,000

[1] Totals: East side, 143,780 acres; west side, 46,230 acres; entire valley 283,550 acres.

In Carson Valley, most of the floor receives between 8 and 12 inches of precipitation. The soil is highly permeable and the depth to ground water is shallow over much of the area. Moreover, in flood-irrigated areas, winter precipitation that is stored as soil moisture is flushed down to recharge the shallow water table in the early spring when irrigation water is first applied. Consequently, more than 3 percent of the precipitation in these areas probably becomes recharge. The Eakin-Maxey technique probably underestimates significantly the magnitude of recharge derived from precipitation that falls on the floor of a wet basin like Carson Valley. Also, the method was designed for application to an entire basin, and the specific location within the basin where the "Eakin-Maxey recharge" takes place is unspecified. This fact makes the estimation of recharge on a cell-by-cell basis, as required for a ground-water model, fairly tenuous.

The basic problems of rejected recharge and probable underestimation of recharge on the valley floor, combined with the fact that the hydrologic regimen of the area is dominated by a through-flowing river, suggest that this technique should be used in Carson Valley only to obtain crude estimates of the amounts of recharge that might be contributed from the mountain areas on the east and west sides of the basin. The ground-water flow model, discussed in a later section of this report, can account for relatively complex interactions between surface-water flows, evapotranspiration, and gains to and losses from the basin-fill reservoir.

The potential recharge is presented in table 6 for comparison with values obtained in the following sections, which estimate sources of inflow to and outflow from the entire basin-fill reservoir as shown on plates 1 and 2, which extends downward to the bedrock basement of Carson Valley.

Surface Inflow

East and West Forks of Carson River

Streamflow entering Carson Valley averages 280,000 acre-ft/yr for the East Fork near Gardnerville (44 years of record, 1939-83) and 80,000 acre-ft/yr for the West Fork at Woodfords (45 years of record, 1938-83).

Runoff from Perennial Drainages

Table 2 lists estimates of average annual runoff from the major perennial streams in the area, which are estimated to total about 18,000 acre-ft/yr on the basis of measurements described in the earlier section on "Streamflow From the Mountain Block."

Recharge to the ground-water basin from these perennial drainages results from infiltration of streamflow into alluvial-fan deposits and into valley-floor deposits where the streamflow is diverted to the irrigation system at the periphery of the valley floor. Some of this streamflow is consumed by evapotranspiration during irrigation, and some is removed from the system as outflow by way of the Carson River.

Runoff from Ephemeral Drainages

Average runoff for ephemeral drainages can be roughly estimated using emperical relations such as those described by Moore (1968). Total runoff from the mountains surrounding Carson Valley has been estimated to be about 24,000 acre-ft/yr (Nevada State Engineer's Office, 1971, p. 57). About 18,000 acre-ft of this is accounted for by flow from the perennial streams (table 2); the remaining 6,000 acre-ft is supplied by flow in ephemeral drainages. During most years, amounts of flow in these drainages are small, and appreciable runoff occurs only during exceptionally wet years or following severe storm events.

Runoff from Eagle Valley

Runoff from the Clear Creek drainage has averaged about 3,900 acre-ft/yr (U.S. Geological Survey, 1970, p. 72; 15 years of record, 1948-62). This runoff enters the Eagle Valley drainage basin and is used for irrigation. Part of it is lost to infiltration and enters the Carson Valley basin-fill reservoir as subsurface inflow (discussed later), and part is lost to evapotranspiration. The remaining runoff that reaches the Carson River is minor in comparison with the magnitude of river flow.

Subsurface Inflow

Underflow from Bedrock to Basin Fill

A significant quantity of recharge reaches the basin-fill reservoir by subsurface flow from the bedrock along the margins of the valley. The precise quantity is difficult to estimate because hydraulic gradients and conductivities are generally not well known at the margin of the basin. Other investigators (Worts and Malmberg, 1967, p. 16; Rush, 1967, p. 18; and Harrill and Moore, 1970, p. 62) have assumed that subsurface flow across the contact between bedrock and valley fill may compose between 5 to 20 percent of the estimated potential recharge. If this same "rule-of-thumb" approximation is applied to Carson Valley, then subsurface flow across the contact there would be between 2,500 and 10,000 acre-ft/yr. However, much of the mountain-front area in Carson Valley is mantled by thick accumulations of highly permeable grus (weathered granitic material), and more water may cross the contact in these areas than in other Nevada basins (Glancy and Katzer, 1975, p. 49). Runoff data from perennial streams (table 2) can be used to evaluate this possibility.

The nine drainages listed in table 2 can be considered as small hydrologic systems to which all inflow is supplied by precipitation, and from which outflow can occur as runoff, subsurface flow, or evapotranspiration. An average of about 41 percent of the precipitation (inflow) to these basins becomes runoff. The percentage that is consumed by evapotranspiration is not directly known but can be estimated by evaluating the extremes of the data. The percent of precipitation accounted for by runoff ranges from 70 to 20 percent. If this variation were due largely to factors that affect infiltration such as permeability and slope, then the basins with the highest percentages of runoff could be assumed to have minor or negligible subsurface outflow. The three highest percentages of runoff ranged between 60 and 70 percent. If subsurface outflow is assumed to be negligible in these basins, then all of the remaining outflow would be by evapotranspiration, and would equal 30 to 40 percent of the precipitation. Assuming this percentage of evapotranspiration to be representative, then on the average, about 40 percent of the precipitation would be accounted for by runoff, 30 to 40 percent by evapotranspiration, and the remaining 20 to 30 percent by subsurface outflow.

The relationship discussed above can be applied to bedrock areas of the valley, which include that part of the drainage basin receiving more than (1) 15 in/yr of precipitation on the west side, (2) 15 in/yr on the southeast side, (3) 16 in/yr on the northeast side, and (4) 10 in/yr on the south side (see plates 1 and 2). Subsurface flow from the bedrock to basin fill may range from 19,000 to 30,000 acre-ft/yr on the west side and from 18,000 to 27,000 acre-ft/yr on the east side. The total for Carson Valley would then be between 37,000 and 57,000 acre-ft/yr. This represents a significant increase over the reconnaissance estimate of 2,500 to 10,000 acre-ft/yr. Therefore, the lower value of 37,000 acre-ft/yr will be used for this study.

Table 2 lists the discharges of six springs that are believed to be supported primarily by subsurface flow from bedrock to valley fill. The total flow of 5,200 acre-ft/yr is the only measured evidence in direct support of subsurface flow. All of the listed springs are on the west side of the valley, where the subsurface flow across the contact is estimated to be between 19,000 and 30,000 acre-ft/yr. If the measured spring discharge is considered to represent only a part of the total subsurface inflow on the west side of the valley, then the measured flow is at least compatible in magnitude with the estimates used in this report.

Ground-Water Inflow to the Drainage Basin

Ground-water inflow at the surface-water gages on the East and West Forks of the Carson River, and along most of the drainage-basin boundary, is considered negligible. The exception is inflow from the Clear Creek drainage in Eagle Valley, which was estimated by Worts and Malmberg (1966, table 9) to be about 600 acre-ft/yr; their value is used herein.

Outflow

Mainstem Outflow

Outflow measured at the Carson River gage near Carson City has averaged 291,000 acre-ft/yr (44 years of record, 1939-83).

Evapotranspiration

Evapotranspiration from areas of irrigated crops and irrigated native pasture grass is by far the largest form of ground-water discharge from the valley. A survey of phreatophyte distribution in the valley (figure 9) shows that rabbitbrush also uses large amounts of water in some places on the valley floor, consuming up to 1.2 ft/yr (Gregg Berggren, U.S. Geological Survey, written communication, 1982). The most vigorous stands of rabbitbrush are in nonirrigated parts of the valley floor in the Johnson Lane area and east of the Douglas County airport; these stands also contain subordinate saltgrass and, locally, greasewood. Farther eastward, these stands become less vigorous and ultimately terminate as depth to water increases. On the western alluvial fans, rabbitbrush is mixed with vigorous stands of bitterbrush. However, depth to water in these areas is probably greater than the maximum root depth of rabbitbrush; thus, the plants in these areas cannot be considered true phreatophytes. Consumptive use of ground water on the western alluvial fans is assumed to be negligible compared to that of the irrigated crops and phreatophytes.

Figure 9 shows the distribution of rabbitbrush and alfalfa plus native pasture grass. Small isolated growths of ash, willow, and cottonwood occur within the valley; however, compared to the far larger areas of rabbitbrush and irrigated lands, their total water consumption is minor.

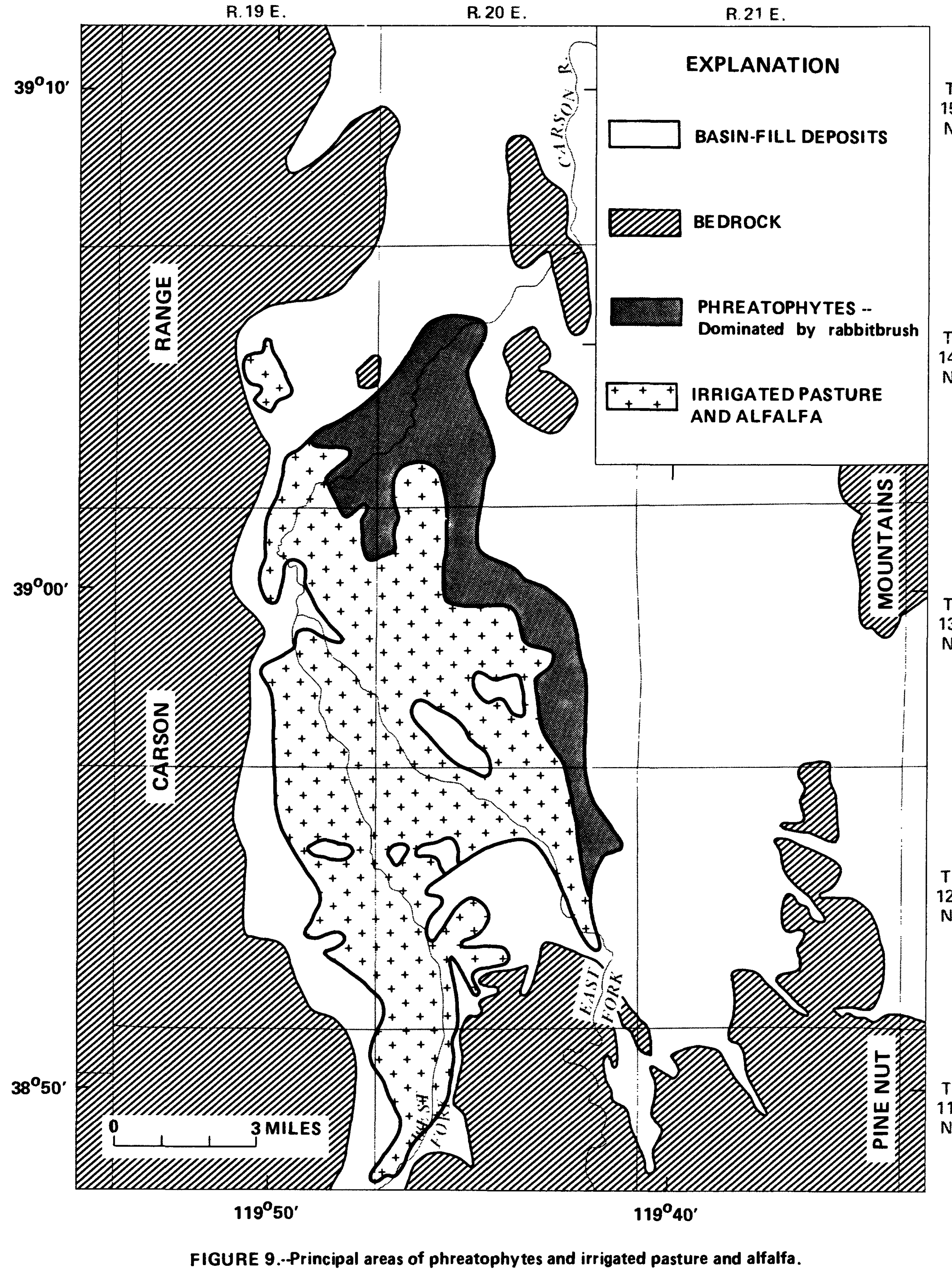


FIGURE 9.--Principal areas of phreatophytes and irrigated pasture and alfalfa.

Previous workers have made differing estimates of evapotranspiration rates for crops in Carson Valley. Piper (1969, fig. 1) and Glancy and Katzer (1975, table 30) calculated evapotranspiration as the difference between known inflow and outflow, whereas Guitjens and Mahannah (1972, p. 12) and Pennington (1980, p. 46) applied pan-evaporation measurements with crop coefficients to obtain consumptive-use rates. The data collected by Pennington are closest in time to the model calibration period and are considered herein to be most representative of long-term evapotranspiration; they are therefore used in this report for estimating consumptive use. As listed in table 7, irrigated crop lands and areas of phreatophytic rabbitbrush total about 62,000 acres. Precipitation falling on this area is estimated to be about 46,000 acre-ft/yr.

About 31,000 acres of basin-fill reservoir is covered by stands of xerophytes, primarily sagebrush with some bitterbrush. Precisely determined use rates for this type of vegetation are not available; however, Loeltz and others (1949, p. 35) used an estimated average value of 9 in/yr to satisfy evapotranspiration requirements in the Martin Creek drainage basin of Paradise Valley, Nev. Applying this rate, a volume of 23,000 acre-ft/yr is calculated for evapotranspiration by xerophytes (table 7). An estimated 9.5 in/yr of precipitation falls on the basin-fill reservoir in the area of xerophytic vegetation, producing a volume of about 24,000 acre-ft/yr.

Table 7 lists the various estimates of evapotranspiration. A total of about 200,000 acre-ft/yr of potential ground-water outflow is caused by evapotranspiration and evaporation from the surface of the basin-fill reservoir. This is a potential loss because evapotranspiration rates are a function of depth to water, decreasing as depth to water increases and becoming zero when depth to water exceeds the maximum root depth of the crops and phreatophytes. As shown in figure 4, depth to water increases away from the valley floor, and the actual evapotranspiration is less than the potential evapotranspiration. Again, a ground-water model can be used to apply the potential evapotranspiration rates as a function of depth to water, which is the best means to accurately estimate actual evapotranspiration.

Evaporation from Open-Water Bodies

Glancy and Katzer (1975, p. 64) estimated valley-wide evaporation from open-water bodies to be 2,800 acre-ft/yr (an estimated 1,100 acres of water, at a net rate of 2.5 ft/yr). This value was assumed to be sufficiently accurate for the purposes of this study.

Ground-Water Outflow

Ground-water outflow at the Carson River gage and along the drainage-basin boundary is considered negligible.

TABLE 7.--*Estimated potential evapotranspiration and evaporation from basin-fill reservoir for average long-term conditions*

Type	Area (acres)	Evapotranspiration: Rate (feet per year)	Evapotranspiration: Volume (acre-feet per year)
Evapotranspiration:			
Irrigated land	46,000	3.52	160,000
Phreatophytes (primarily rabbitbrush)	15,900	1.2	19,000
Xerophytes (primarily sagebrush and greasewood)	31,000	.75	23,000
Evaporation, surface-water bodies	1,100	2.5	2,800
Total (rounded)	94,000	—	200,000

Water Budget

A water budget for a basin compares independent estimates of all major sources of inflow to and outflow from the basin. Of first concern is a budget representative of average long-term conditions, often called steady-state conditions. For such conditions, the hydrologic system is considered to be in equilibrium; thus, average total inflow should equal average total outflow, over the long term. However, errors in estimates for individual budget components often result in an imbalance between the total estimated inflow and outflow for a basin. A comparison of differences in the estimated flows can provide insight with regard to potential sources and relative magnitudes of error in the individual budget terms.

Table 8 gives the estimated long-term budget for Carson Valley. One of the most significant things illustrated by this budget is that the estimates of both inflow and outflow by way of the Carson River substantially exceed the other components. Consequently, the hydrologic regimen of the basin-fill reservoir is dominated by the river. One result of this is that recharge to the basin-fill reservoir is not a fixed quantity; instead, it fluctuates depending on the state of the ground-water system and the degree of continuity between the river and the basin-fill reservoir. These complex relations are best evaluated using mathematical models such as the ground-water flow model described in a later section of this report.

TABLE 8.--*Estimated long-term water budget for basin-fill reservoir, under present-day conditions*

Component	Acre-feet per year
INFLOW	
Precipitation on basin-fill reservoir (table 6)	70,000
Surface inflow:	
East Fork Carson River (p. 37)	280,000
West Fork Carson River (p. 37)	80,000
Runoff, perennial drainages (table 2)	18,000
Runoff, ephemeral drainages (p. 37)	6,000
Subsurface inflow:	
Underflow from bedrock to valley fill (p. 38)	37,000
Inflow from Eagle Valley (p. 39)	600
Total (rounded)	490,000
OUTFLOW	
Surface outflow, Carson River (p. 39)	291,000
Potential evapotranspiration, rounded (table 7)	200,000
Evaporation from surface-water bodies (table 7)	2,800
Total (rounded)	490,000
IMBALANCE	0

Runoff and subsurface inflow, as shown in table 8, total about 61,000 acre-ft/yr. This value compares fairly well with a potential recharge of 47,000 acre-ft/yr, which was estimated for the east and west sides of the valley using the Eakin-Maxey method (table 6). The general agreement of two independent methods for estimating inflow to the basin-fill reservoir creates more confidence in these estimates.

Major differences between the budget of table 8 and that developed by Glancy and Katzer (1975, p. 66) exist because Glancy and Katzer (1) used different areas to estimate precipitation, (2) used a different distribution of precipitation to estimate potential recharge using the Eakin-Maxey method, (3) estimated evapotranspiration as the difference between total inflow and all other components of outflow, and (4) used different reference periods for records of streamflow.

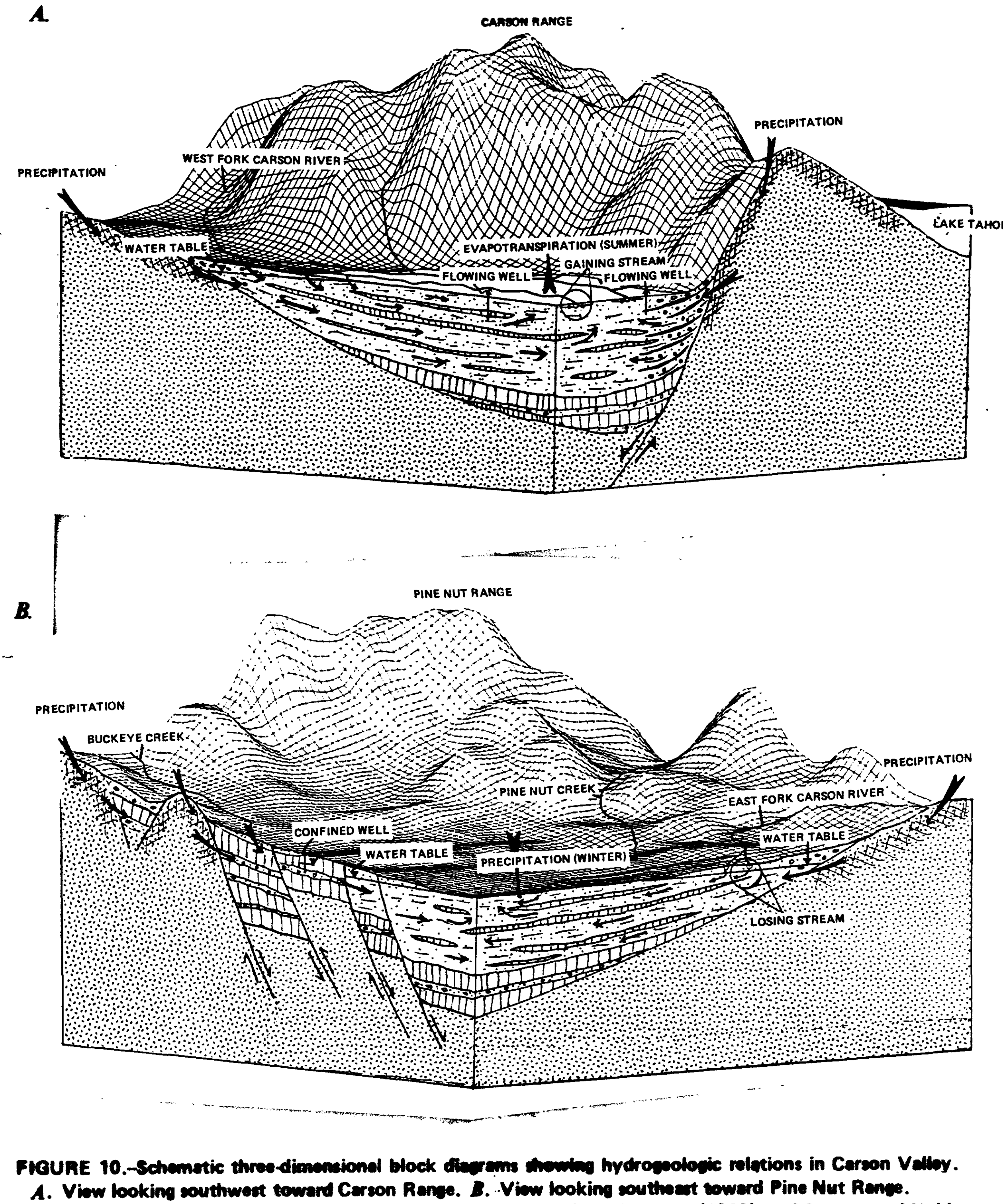


FIGURE 10.–Schematic three-dimensional block diagrams showing hydrogeologic relations in Carson Valley. *A*. View looking southwest toward Carson Range. *B*. View looking southeast toward Pine Nut Range. Subsurface geology inferred from information given by Maurer (1984), Moore (1969), and Stewart and Noble (1979), and from drillers' logs.

SUMMARY OF HYDROLOGIC RELATIONS

Figure 10 shows the hydrogeologic relations that control the flow systems in the Carson Valley ground-water basin. Precipitation on mountain blocks surrounding the valley floor recharges basin-fill reservoirs (1) by percolation through fractures and weathered zones in the granitic bedrock and subsequent lateral movement into the alluvial-fan deposits, and (2) by runoff from the mountain block and subsequent percolation into the alluvial-fan deposits and into the water-table aquifers when the streamflow enters the ditch system on the valley floor. Recharge by way of the alluvial-fan deposits probably reaches both the water-table and confined aquifers beneath the valley floor, as evidenced by water-level fluctuations observed in shallow artesian and water-table wells at the base of alluvial fans along the west side of the valley.

Recharge from the Pine Nut Mountains probably occurs in a manner similar to the processes described for the Carson Range, along subsurface fractures and weathered zones in the bedrock and into the Tertiary sediments. However, runoff and precipitation that falls on the exposed Tertiary sediments must percolate through thick fine-grained units, or downward along the numerous fault zones, before reaching coarser beds.

EXPLANATION

BASIN–FILL DEPOSITS DOMINATED BY COBBLES AND GRAVEL

BASIN–FILL DEPOSITS DOMINATED BY SAND AND SILT

BASIN–FILL DEPOSITS DOMINATED BY CLAY––Thick units overlying bedrock are Tertiary deposits

POORLY SORTED ALLUVIAL–FAN DEPOSITS

BEDROCK––Crosshatches indicate weathered or fractured zones

MAJOR FAULT

GROUND–WATER FLOW PATH

FIGURE 10.--Continued.

Accordingly, recharge by this process is probably small. The rate of flow within the Tertiary sediments is probably slow, as shown by the lack of fluctuation in water levels on the east side even during extremely wet years. Exactly how water moves from the Tertiary sediments to Quaternary aquifers beneath the valley floor is not clearly understood, but a diffuse zone of faulting probably offsets the fine-grained sediments, providing an avenue for flow into unconsolidated basin-fill deposits beneath the valley floor.

Recharge to the confined aquifer in the central part of the valley floor is gained partly from water transmitted through the alluvial-fan deposits on the west side of the valley and Tertiary sediments on the east side, and partly from percolation of surface-water flow in the upstream areas of the valley floor. The south-to-north dip of fluvial sediments beneath the valley floor and the presence of clay lenses probably cause the confined heads observed in the central and northern parts of the valley. Upward leakage from the confined aquifer to the water-table aquifer is probably significant, considering the sporadic occurrence of the confining unit.

Figure 11 shows long-term monthly surface-water inflow and outflow, precipitation, and evapotranspiration for Carson Valley. From November to March, the total outflow is greater than the total inflow. During these months, evapotranspiration rates are very low, precipitation on the valley floor and surrounding mountain blocks is at a maximum, and surface-water diversions are confined to the ditch system. Well hydrographs also show an increase in ground-water storage during winter months, indicating that ground-water recharge occurs at this time.

From April to November, evapotranspiration rates are high, precipitation is low, and surface-water outflow decreases to less than the total surface-water inflow. This condition generally begins in mid-March, when the evapotranspiration rate exceeds the precipitation rate. However, flood irrigation also begins at this time, with diverted streamflow spread over a large part of the valley floor. Percolation to the water table from surface-water flow is important in increasing storage in the shallow ground-water reservoir, especially on the east side of the valley.

NUMERICAL MODEL

This section of the report deals with integrating the previously described hydrogeologic characteristics into a numerical model that will simulate streamflow and ground-water flow and tabulate calculated hydraulic heads, flow volumes, and ground-water storage. The purpose of the model is to: (1) test our understanding of the hydrogeologic processes in the basin and our estimates of their hydrologic properties, (2) simulate, on a large scale, interaction between the surface-water and ground-water systems, and (3) provide a preliminary tool for planners to assess the possible effects of development alternatives.

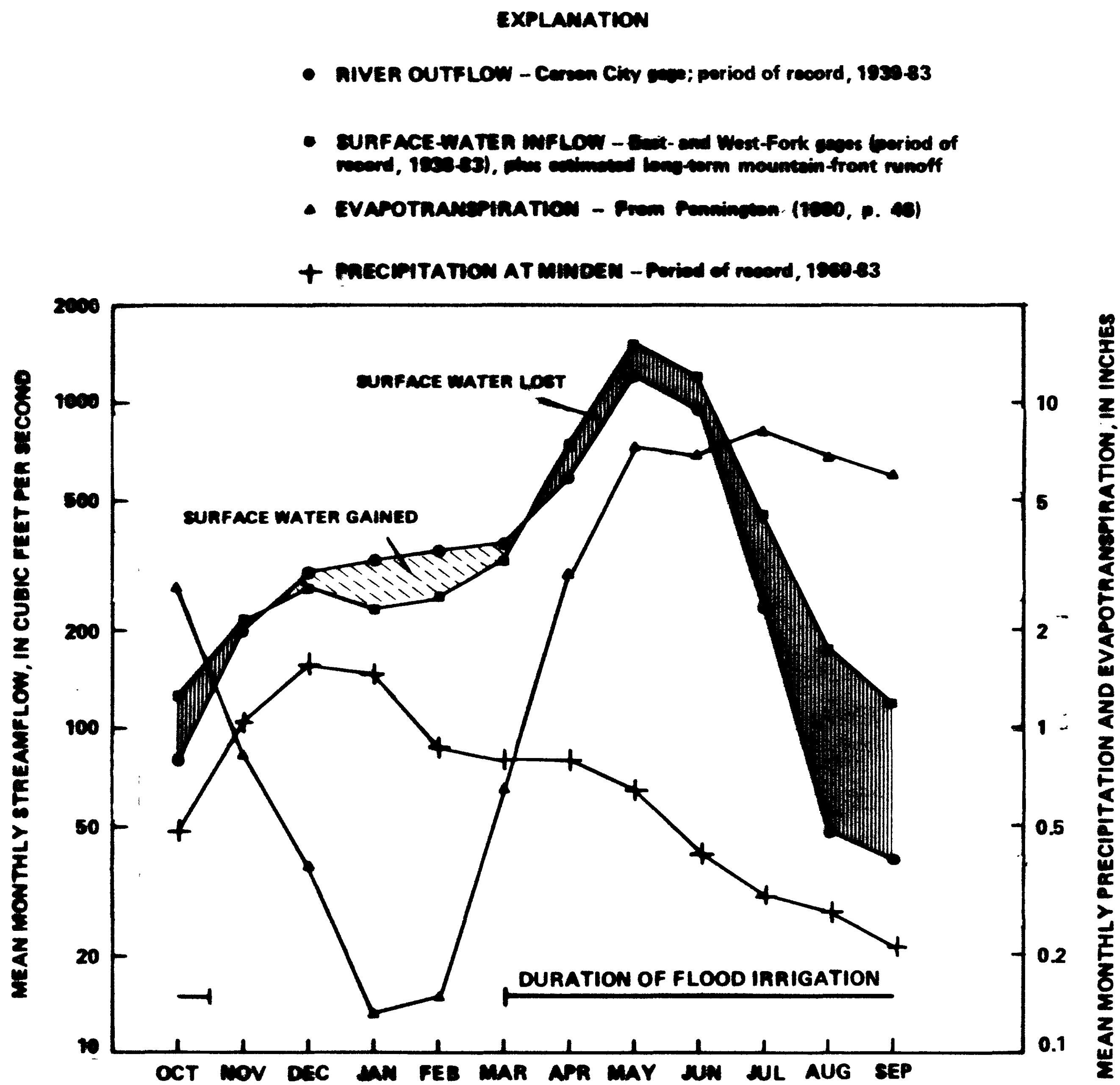


FIGURE 11.--Long-term mean monthly surface-water inflow, surface-water outflow, precipitation, and evapotranspiration; and normal duration of flood irrigation.

The computer program used is described in detail by McDonald and Harbaugh (1984). Briefly, the program simulates three-dimensional ground-water flow with a partial differential equation. This equation uses hydraulic conductivity, specific yield or storage coefficient, and hydraulic head to calculate the changes in storage and hydraulic head with time, given the stresses (rates of inflow and outflow) applied to the system as recharge, pumping, and evapotranspiration. The stresses are applied for a period of time that is specified by the user, which is called a stress period. The equation is solved by a finite-difference technique described by McDonald and Harbaugh (1984, p. 7-30) using the strongly implicit procedure. The finite-difference technique uses a grid that is superimposed over the modeled area, and each cell of the grid represents the hydrogeologic setting of the modeled area within that cell. Input data are estimated for each cell in each layer, and consist of initial head altitude, altitude of the top and bottom of the cell, hydraulic conductivity and specific yield (or storage coefficient for confined cells), vertical conductivity between each layer, and estimates of recharge, evapotranspiration, pumpage, and streambed conductivity and altitude at cells where these stresses occur. The strongly implicit procedure simultaneously solves the flow equation for each row and column of cells in the grid matrix, applying the stresses estimated by the user at each cell. Thus, the simulated head should approximate the head observed in each cell if the estimates of (1) stresses applied to the system and (2) hydraulic properties are reasonable.

The model incorporates several subroutines that independently handle calculations of evapotranspiration, streamflow, recharge, pumpage, initial head, aquifer thickness, and aquifer conductivity and storage. This procedure allows the user to easily make changes in each individual subroutine.

All numerical models are limited by (1) the inadequacy of a generalized conceptual model to accurately portray all the complexities of the natural system and (2) deficiencies of existing data to accurately describe the system. The Carson Valley model was designed to be used as a preliminary tool for testing estimates of the geohydrologic characteristics and processes in the valley, and to show the effect of large-scale changes in pumpage and land use on water levels and ground-water storage in the valley and on Carson River outflow from the valley. If the model is applied for other uses, the effect of generalization and lack of data points could produce significant inaccuracies.

Another problem inherent in all models is the nonuniqueness of their solutions. An acceptable calibration could be obtained using a completely different set of values for recharge, evapotranspiration, stream-cell conductance, and hydraulic conductivity. The values used herein are thought to represent the best-fit compilation of available data. Continued data collection during the period of increasing development in the valley will provide a means to check the uniqueness of the model and refine the model calibration.

Model Configuration

The outside boundary of the model grid superimposed on Carson Valley coincides with the basin-fill reservoir (see plates 1 and 2) that was used for water-budget estimates.

A 1-mi^2 grid was used for the model because it facilitated estimation of input data at a manageable number of cells, described the physical boundaries of the valley fairly well, and allowed fairly close estimation of hydraulic head at each cell using the existing distribution of observation wells (see figure 12). The scale of simulation is rather large, and the input data are averaged over a 1-mi^2 area. Thus, for example, drawdown of individual wells and application of irrigation water to individual fields cannot be simulated.

Initially, a 0.25-mi^2 grid was used, but the much larger number of cells was cumbersome and required much interpolation of input data, given the distribution of available data points. Considering the preliminary nature of the model, the 1-mi^2 grid was considered more expedient and of adequate accuracy for the intended uses.

Two layers were used in the model to simulate the Quaternary unconsolidated deposits in the valley (see figure 12). The upper layer, representing the unconfined aquifer, is about 200 feet thick and immediately underlies the valley floor. Layer one (the upper layer) thins to less than 100 feet on the west side of the valley, to conform to the shallow artesian aquifer found beneath the alluvial fans there.

Layer two represents the remainder of the Quaternary deposits beneath the upper layer and extends eastward to the outcrop of Tertiary sediments. The depth-to-bedrock map (plate 2) was used to estimate the total thickness of layer two at each cell.

The confining layer between layers one and two is represented in the model by a vertical conductivity value that controls ground-water flow between the upper and lower layers. This value was calculated from the estimated proportions of coarse and fine material present in each cell, as described previously. The confining layer is assumed to be thin relative to the thickness of the aquifers, so that storage and horizontal flow in the confining bed can be ignored.

More than two layers could have been used to represent the Quaternary deposits. For example, a thin surface layer could be used to accommodate the pumping of shallow wells, evapotranspiration, recharge, and streamflow, possibly giving slightly different results than those for the two-layer model. However, the main concern for this preliminary model was the interaction between the confined and unconfined aquifer. This concern and the extent of available data made a two-layer model more practical. Refinement of the working model to a three-layer model would be possible after more data are collected.

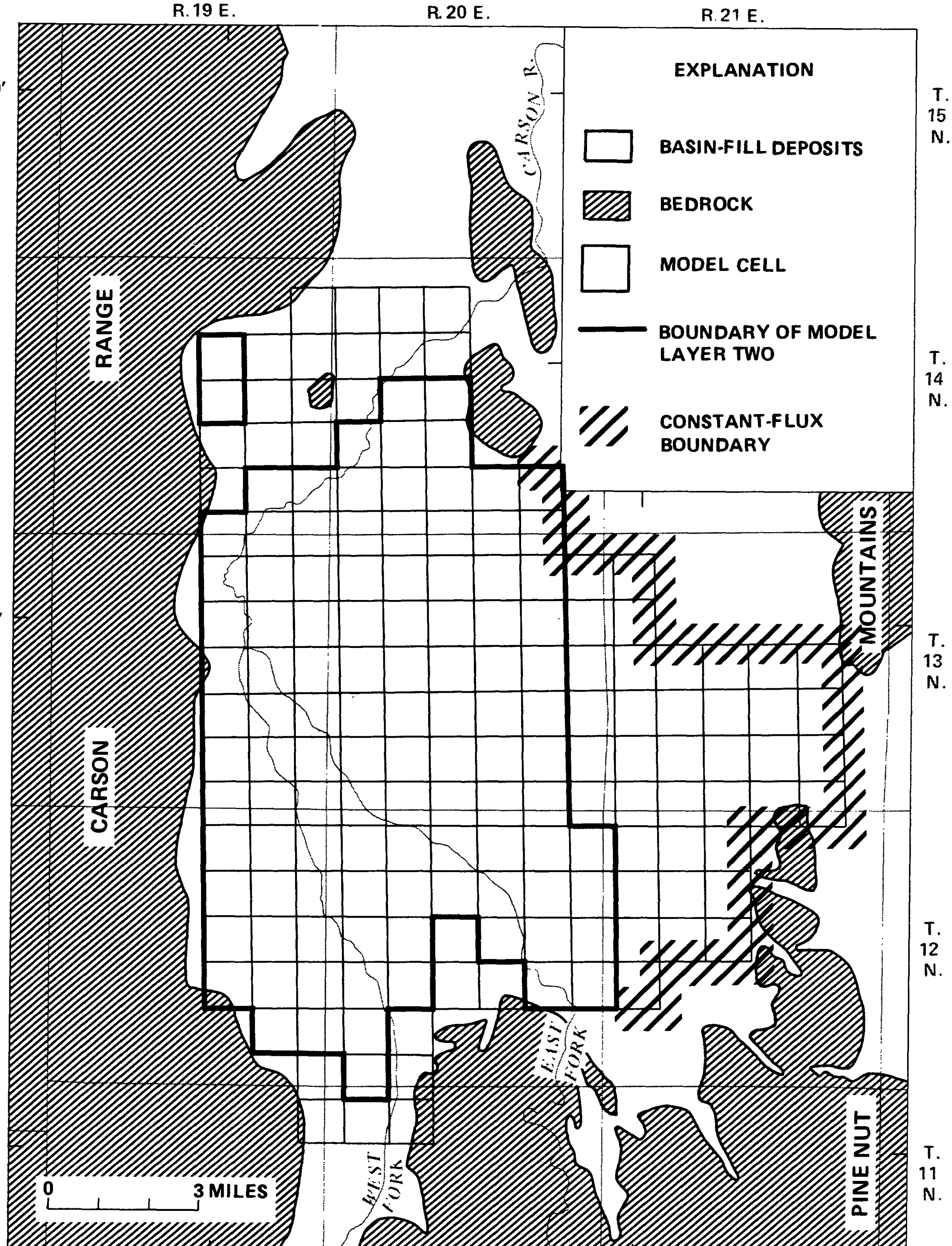


FIGURE 12.--Grid network used in numerical model.

As discussed previously, the Tertiary sediments are composed of thin coarse layers that transmit most of the ground water, and thicker clay layers that act as confining beds. Because the thickness and extent of these layers are unknown, the Tertiary sediments are treated as a single unit having a lower hydraulic conductivity than that of the Quaternary basin-fill deposits. The Tertiary sediments are assumed to compose the entire thickness of basin fill east of their point of outcrop; west of this point, they are assumed to be thin relative to the unconsolidated Quaternary deposits in the central part of the basin. This might not be true at all points in the western part of the basin if the Tertiary sediments are as much as 1,000 feet thick, as mentioned in the section on lithologic units. The effect of a thick section of Tertiary sediments on the west side of the basin is evaluated and discussed in the section on model sensitivity.

Methods used for Calibration and Predictive Simulations

The model was calibrated by first making steady-state simulations in which neither pumpage nor change in storage is considered. The term "steady-state" is usually applied to basin conditions as they existed before development by man. In Carson Valley, flood-irrigation ditches and wells for stock water have been in operation for more than 80 years. Annual precipitation on the valley floor ranges from 6 inches in dry years to more than 18 inches in record wet years. Superimposed on the wet and dry cycles is the seasonal variation from flood conditions in the spring to dry conditions in the fall. Thus, the system is constantly fluctuating. Despite these variations, no measurable, long-term change in storage can be detected for the past 30 years. Accordingly, the system was considered to be in a steady-state condition during this study.

Ground-water models are usually calibrated using a long-term change in water-levels. The lack of a measurable change in ground-water storage since 1956 requires a transient calibration using seasonal variations in recharge, ground-water storage, evapotranspiration, and pumpage. Data were collected for water years 1981 through 1983 (from October 1980, a dry year, through September 1983, a record wet year), allowing measurement of the maximum fluctuation in ground-water storage that might be expected until further development places a larger stress on the system. The water year can be conveniently divided into quarterly stress periods during which stresses on the hydrologic system are relatively constant: October through December, January through March, March through June, and June through September, representing fall, winter, spring, and summer conditions, respectively.

During all phases of calibration, recharge was assumed to be known to within a factor of two, whereas hydraulic-conductivity estimates were shown to vary by at least an order of magnitude (a factor of 10). Thus, during calibration simulations, adjustments were made only to the conductivity estimates, while recharge was held constant. Hydraulic conductivity was adjusted until a reasonable fit between observed and calculated hydraulic heads was obtained. Next, streambed conductivities were adjusted until a reasonable match of calculated and measured Carson River outflow was obtained. Hydraulic conductivity was further adjusted until a reasonable agreement between observed and calculated head was obtained for steady-state and transient simulations with the same conductivity distribution. Predictive simulations were conducted by combining (1) the final distribution of vertical and horizontal hydraulic conductivity, streambed conductance, recharge, and evapotranspiration obtained from steady-state calibration, with (2) storage values obtained during transient calibration, and applying pumpage for a 45-year period, followed by a 45-year recovery period.

Boundary Conditions, Data Input, and Initial Conditions

Most of the outside perimeter of the model grid was simulated as a no-flow boundary. The mountain blocks have low overall hydraulic conductivity, and the edge of the model grid approximates the contact between bedrock and valley fill. As described later, subsurface flow from the mountain blocks is added as recharge to the basin-fill aquifers, so the no-flow boundary is considered appropriate there. Along the eastern boundary, a distance of several miles exists between the model boundary and the bedrock contact. Due to the lack of observation wells in that area, hydraulic-head values were not available east of the boundary. Hydrographs of wells near the eastern boundary show virtually no seasonal water-table fluctuations, implying a nearly constant flux across this boundary (figure 12). An additional row of cells was added to extend the model boundary far enough away from existing wells to reduce the boundary effect of pumping wells during simulations, yet close enough so that a constant-flux boundary would accurately portray the hydrologic setting in that part of the valley.

Figure 13 shows the distribution of long-term recharge used for the steady-state simulations. Subsurface inflow across the contact between bedrock and valley fill (table 8) is applied to all boundary cells by dividing the inflow by the number of cell faces that are directly downgradient from each part of the drainage basin, as described earlier. Runoff from each perennial stream is applied in the same manner to cells downgradient from each perennial basin, and runoff from ephemeral stream basins is apportioned by area to cells downgradient from ephemeral drainages. The inflow from the Eagle Valley basin (table 7) was distributed among cells along the northern boundary of Carson Valley.

For cells representing land with irrigated crops or phreatophytes (those cells receiving more than 0.6 ft^3/s of recharge and western boundary cells), the total precipitation received by those cells, about 46,000 acre-ft/yr, is distributed as recharge. For cells representing land with xerophytic vegetation (cells receiving 0.02 ft^3/s of recharge and eastern boundary cells), the use rate estimated by Loeltz and others (1949, p. 5) was applied to precipitation as described previously (table 9), and the remaining precipitation, about 1,000 acre-ft/yr, was distributed as recharge.

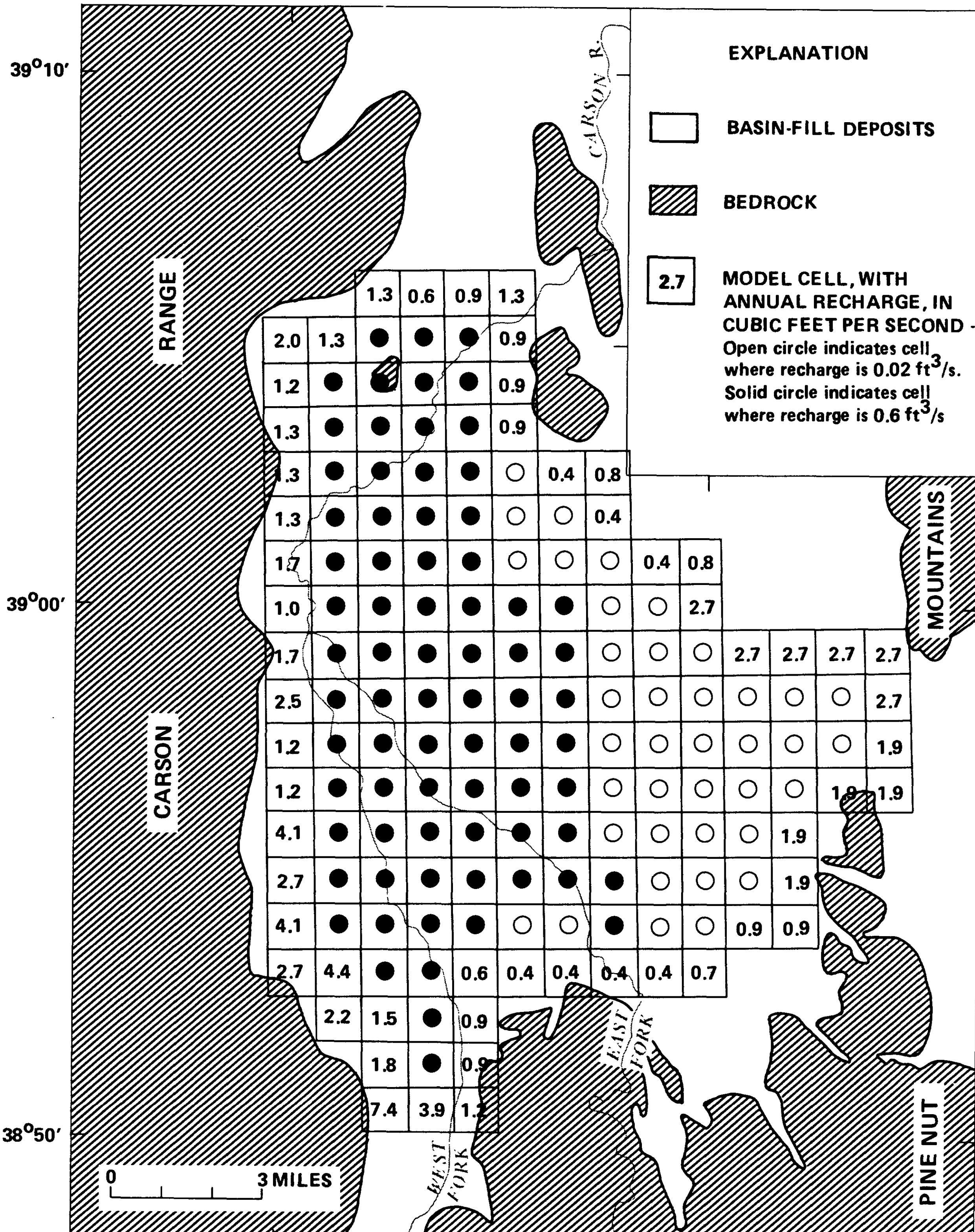


FIGURE 13.--Distribution of estimated average annual recharge for long-term conditions, as used in numerical model.

For water years 1981-83, estimated recharge of sewage imported to the valley and of sewage generated within the valley, and secondary recharge of pumped water, were added to recharge from precipitation in cells where sewage was applied or where wells were pumped.

Evapotranspiration is simulated at those cells (figure 14) where rabbitbrush is an important water user and at cells where native grass or alfalfa is present (see figure 9). The actual evapotranspiration rate is a linear function of the depth to water--it is maximum when the water table is at land surface, and decreases to zero at the extinction depth for plant consumption. The extinction depth simulates the maximum reach of the root zone of phreatophytic plants. The maximum root depth of alfalfa is about 35 feet (Zimmerman, 1969, table 20). This value was used because root depths are probably at a maximum where depth to water is large but where irrigation water is available for continued growth. The same extinction depth was used for cells representing areas with rabbitbrush, because few data on their maximum root depth are available in the literature and because it seems to be limited in occurrence by a depth to water of less than 30 to 40 feet beneath the valley floor.

The streamflow routing package of McDonald and Harbaugh (1984) was modified by David E. Prudic (U.S. Geological Survey, written communication, 1985) to calculate cell-by-cell flow volumes and to more easily simulate the many diversion and tributary-stream sections required by the complex irrigation-ditch system in Carson Valley. Figure 15 shows the model representation of the irrigation system. The representation did not simulate the entire ditch system in the valley but approximated the distribution of flow in the major ditches. This subroutine uses the hydraulic head in the node, the altitude of the streambed, and a conductance value for the stream cell to calculate flow through the streambed. The conductance is given by the following equation:

$$\text{stream-cell conductance} = \frac{(\text{streambed conductivity}) \times (\text{streambed area})}{\text{streambed thickness}},$$

where the stream-cell conductance is measured in feet squared per second, streambed conductivity in feet per second, streambed area in square feet, and streambed thickness (that is, the thickness of streambed deposits) in feet. The volume of water that is gained or lost through the streambed is then applied to the surface-water inflow for each cell, and the surface-water outflow from each cell is calculated.

Several factors present complications in using the streamflow subroutine. Streambed areas range from the large scale of the Carson River down to the individual furrows of a flood-irrigated field. These areas and flow volumes can change rapidly as flow is routed to various ranches, ditches, and fields. Also, the practice of dredging and cleaning ditches changes bed altitudes, thicknesses, and conductivities at differing points and times.

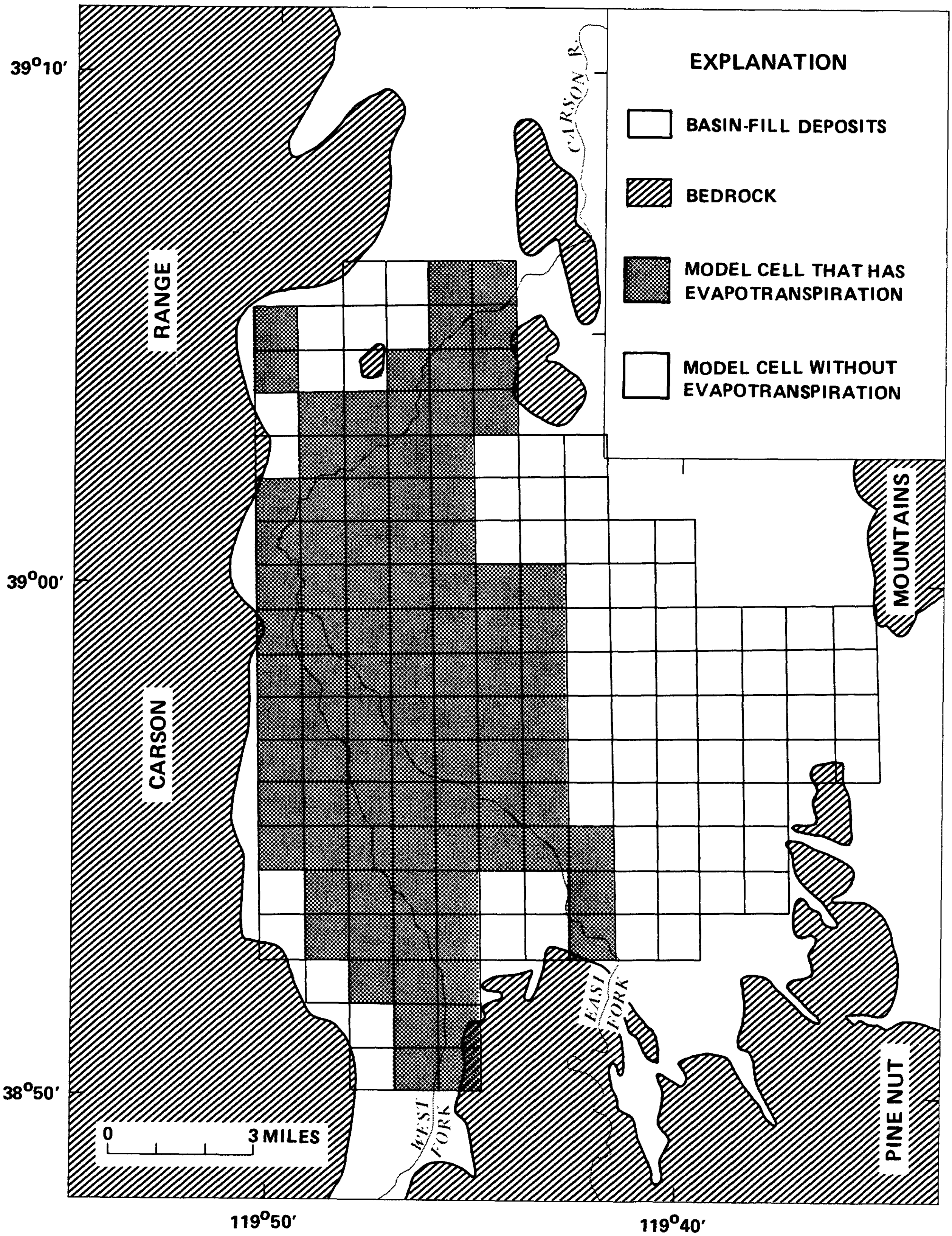


FIGURE 14.--Distribution of evapotranspiration used in numerical model.

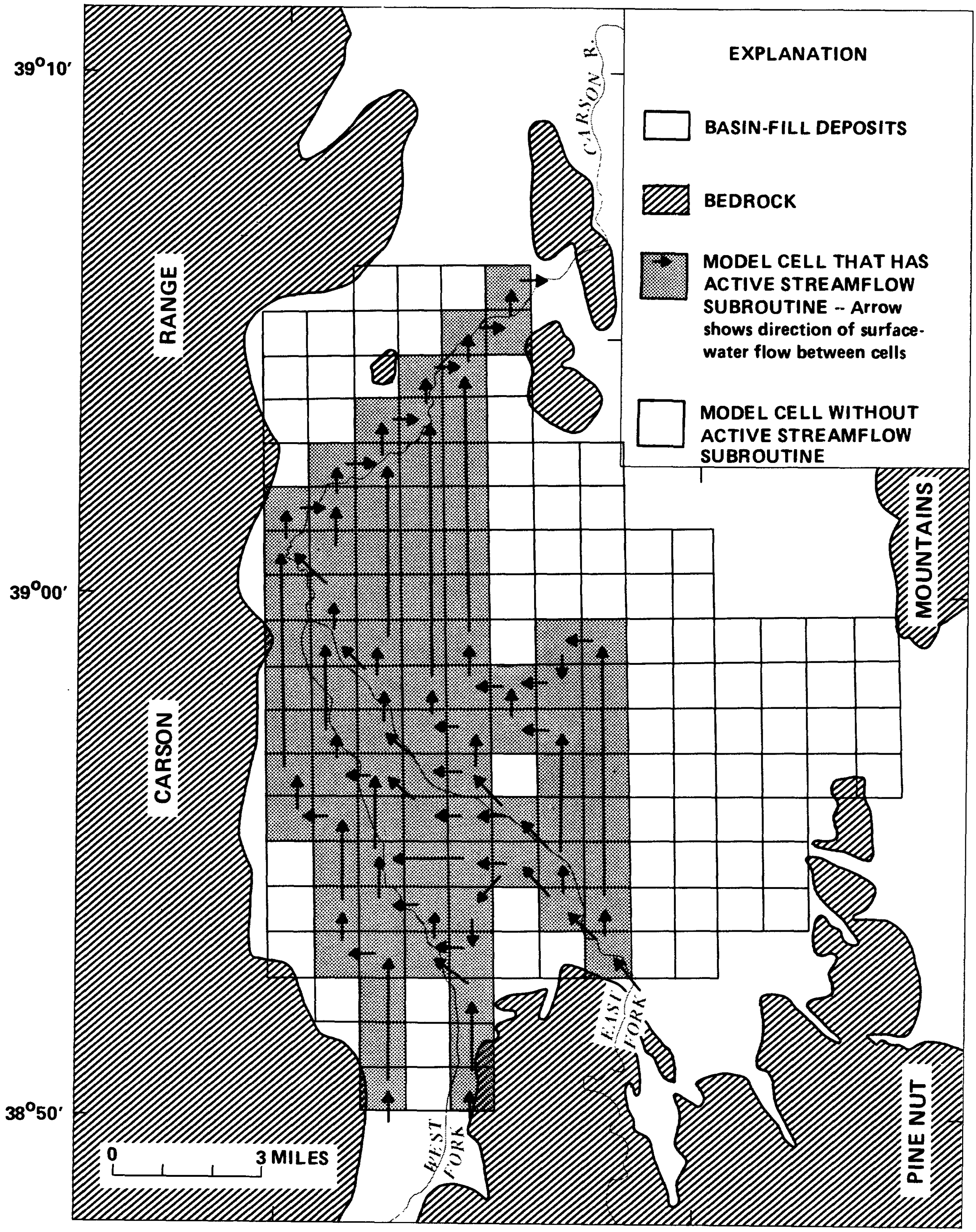


FIGURE 15.--Streamflow routing system used in numerical model.

In lieu of attempting to account for these factors, conductances were assumed to be similar over major parts of the valley floor. Streambed area was assumed to represent the total flooded area in each cell, including streams, ditches, and flooded fields. Due to the frequent dredging of ditches and the practice of flood irrigation, the thickness of streambed deposits was considered to be small and streambed thickness was assumed to be 1 foot. Thus, stream-cell conductance is a function of area; it is high during summer months when flood irrigation increases the streambed area, and low during winter months when flow is confined to the major streams and ditches.

The inclusion of flood-irrigated fields in the streambed-area term causes the conductance to be a function of time. Irrigation applications at an individual field occur five to six times, for a period of 1 to 2 days each, during an irrigation season (Arlan Neil, U.S. Soil Conservation Service, oral communication, 1983). Thus, for a period of 1 year, the stream cell is completely flooded for only about 12 days, or 3 percent of the year, and the resulting conductance of the cell would be only 3 percent of that if the cell were flooded during the entire year.

Streambed altitudes were estimated from 5-foot contour sheets (Genge Aerial Surveys, 1977) at the center of each cell. Average flow volumes for individual ditch systems represented in the model were obtained from Garry Stone (Federal Watermaster's Office, oral communication, 1984) and from estimations made in the field.

Pumpage data were summarized for each stress period and distributed between layers one and two by the percentage of perforations in each layer for each well. The actual amount pumped from each layer depends on the depth of the perforated intervals in the well casing and the relative difference in conductivity between each layer. Pumpage from each layer was assumed to be proportional to the relative length of perforations in that layer. These data were obtained from the driller's log of each pumping well.

The hydraulic conductivity and vertical conductivity of the confining layer for each cell were calculated on the basis of the proportions of coarse and fine material indicated in well logs (figure 7) for that cell. The equations described previously (see "Aquifer Properties") were used, with an initial conductivity of 10^{-4} ft/s for coarse material and 10^{-7} ft/s for fine material. The horizontal and vertical conductivities obtained were used as initial values for the conductivity of layer one and for the vertical conductivity between layers one and two. Due to the lack of data for layer two, a single value of 10^{-6} ft/s, as discussed previously, was used there.

The initial areal distribution of specific yield for layer one was estimated from the values calculated by Dillingham (1980, plates 2 through 8). Because he reports specific yield for the basin-fill material by intervals of thickness ranging from 20 to 100 feet, the specific yield for layer one was estimated by calculating the average of the specific yield mapped by Dillingham (1980) for the various depth intervals represented by the thickness of layer one at each cell. The storage coefficient for layer two was obtained by multiplying the thickness of layer two by $2x10^{-6}$ ft/s, a value found reasonable in many Great Basin valleys (David E. Prudic, U.S. Geological Survey, oral communication, 1984).

The water levels contoured in figures 3A and 3B represent average conditions found in midwinter after recovery from late-fall declines and before the peak produced by spring runoff. These values were used as initial heads for steady-state simulations.

Steady-State Calibration

The initial conductivity distribution in layer one was modified by use of a multiplier to change all the values by an equal amount, thereby retaining the same relative distribution derived from the data on grain-size proportions. A multiplier of 7.5 was found to give the best agreement between observed and simulated heads for cells on the valley floor. This adjustment was thought to be needed because many drillers do not distinguish between fine sand, silt, and clay; instead, they label any fine-grained sediment as clay.

Initial conductivity values calculated for layer one on the east side of the valley, in Jacks Valley, and in cells along the west edge of the valley had to be decreased, sometimes by an order of magnitude, to obtain a reasonable fit of observed versus simulated heads. In these areas, the values calculated by the Theis method provided a better approximation of the conductivity than those derived from grain-size data (see discussion under "Aquifer Properties").

Adjustment on a cell-by-cell basis was required on the east side of the valley. This adjustment was based on geological inferences: lower conductivities were assigned along the ridges of exposed Tertiary sediments, and higher conductivities were used where Pine Nut and Buckeye Creeks enter the valley.

The simulated heads in the Jacks Valley area also were very sensitive to small changes in hydraulic conductivity. Jacks Valley is separated from the Carson River flood plain by low hills that are composed of a mixture of Tertiary sediments and underlying weathered granitic bedrock. The valley floor itself is underlain by alluvial-fan deposits. This mixture of rocks of greatly differing conductivity, along with the large grid size, make estimation of average conductivities in each cell difficult. A value of 10^{-5} ft/s for layer-one cells representing the low hills provided a reasonable match between observed and simulated heads.

The initial conductivity value of 10^{-6} ft/s used for all cells in layer two provided an adequate fit of observed and simulated heads, and therefore was not adjusted.

The stream-cell conductances were adjusted valley-wide until long-term outflow was matched; on the valley floor, the final value was 2.0 ft^2/s. That value was not satisfactory along the east side of the ditch system, however. Those cells required conductances of 1.2 ft^2/s--somewhat less than the value used on the valley floor--to reduce simulated ditch leakage that caused too great an increase in simulated heads in that area. This is due partly to the grid size used in the model. Only the west half of each of these cells is flood-irrigated land; the eastern half is covered with sage and rabbitbrush. Also, during the calibration period, these east-side ditches were not cleaned as regularly by backhoe as were many of those on the valley floor, thereby contributing to a lower conductance.

An equation was developed that used the ratio between the observed and simulated head differences between layers one and two to adjust the vertical conductivity, cell by cell, until a match was obtained. Four iterations were required to obtain a good match, with final values ranging from 10^{-8} to 10^{-11} ft/s.

Inspection of cell-by-cell flow budgets developed during the steady-state simulations indicated that flow directions were consistent with those interpreted from the observed water-level gradients. Ground-water flow moved downward into the confined aquifer (1) along the entire east side of the valley floor, (2) at the south end of the valley where the East and West Forks of the Carson River enter, and (3) along the far west side of the valley. Upward flow from layer two to layer one occurred throughout the valley floor, with rates decreasing toward the east. Total upward flow was about 19,000 acre-ft/yr. Simulated flow between layers one and two is consistent with flow directions indicated by comparisons of confined and unconfined water levels.

The long-term cell-by-cell budget for the ditch-routing subroutine shows losing streams and ditches on the east and south sides of the valley and gaining streams and ditches over most of the valley floor--again, consistent with observed conditions. A net loss of streamflow to the unconfined aquifer of about 44,000 acre-ft/yr was calculated. Thus, surface-water irrigation is a major source of recharge to the shallow ground-water system in the valley.

Evapotranspiration calculated for the steady-state simulation was 148,000 acre-ft/yr for irrigated crops and phreatophytes. This is a significant decrease compared to the 180,000-acre-ft/yr potential evapotranspiration estimated for crops and phreatophytes in table 7.

A revised water budget for the basin-fill reservoir can now be compiled using the values calculated by the model for evapotranspiration and net loss of streamflow from the Carson River system. Table 9 summarizes the values and shows a close agreement between long-term inflow and outflow. Thus, unless compensating errors exist in the estimates, they provide good preliminary values for the basin-fill reservoir in Carson Valley.

TABLE 9.—*Simulated long-term water budget for basin-fill reservoir, under present-day conditions*

Component	Acre-feet per year
INFLOW	
Precipitation:	
Phreatophytic and crop lands (p. 41)	46,000
Xerophytic lands (p. 41)	24,000
Surface water:	
Runoff, perennial drainages (table 2)	18,000
Runoff, ephemeral drainages (p. 37)	6,000
Carson River (net loss calculated by stream-routing subroutine)	44,000
Subsurface inflow:	
Underflow from bedrock to valley fill (p. 38)	37,000
Inflow from Eagle Valley (p. 39)	600
Total (rounded)	170,000
OUTFLOW	
Evapotranspiration:	
Phreatophytic and crop lands (calculated by evapotranspiration subroutine)	148,000
Xerophytic lands (p. 41)	23,000
Evaporation from surface-water bodies (table 7)	2,800
Total (rounded)	170,000
IMBALANCE	0

Budget Estimation for Transient Calibration

Table 10 shows the simulated water budget for Carson Valley during the 3-year calibration period, and incorporates observed surface-water flows and estimated volumes of recharge, pumpage, and imported sewage. Budget elements were estimated on a quarterly basis for each water year for use in the transient calibration of the ground-water model. Changes in storage seen during the dry summer of 1981 served as a check on estimates of budget components.

To estimate seasonal changes in recharge at the model boundaries, the value at each cell calculated for long-term recharge was used and assumed to vary with mountain-front runoff. Runoff, rather than precipitation, was used because much of the precipitation on the mountain blocks is stored in the winter snow pack until spring runoff. Recharge from mountain-block precipitation is assumed to coincide in time with the spring snowmelt that causes an increase in runoff at the gaging station on Daggett Creek.

The long-term flow records for Daggett Creek were used to determine normal distribution of runoff during each quarter in the average water year. Records from 1981-83 at Daggett Creek were used to calculate the percentage of long-term normal runoff for each quarter during the 3-year period. Table 11 summarizes the values and compares them with precipitation on the valley floor at Minden.

As seen from table 11, long-term quarterly runoff from Daggett Creek is almost evenly distributed throughout the year, despite a large seasonal variation in precipitation. Long-term annual recharge was then divided by four to obtain a quarterly value and multiplied by the percentage of annual average streamflow during each quarter to obtain an estimate of recharge received in the quarter in an average water year. This value was then multiplied by the departure from normal runoff at Daggett Creek for each quarter in the 3-year period, to adjust the values to the period 1981-83.

Quarterly precipitation at Minden was assumed to approximate quarterly precipitation throughout the valley floor, which in general coincides with the area receiving less than 10 inches of precipitation per year (plate 1).

Pumpage for agricultural use was estimated from kilowatt-hour data supplied by Sierra Pacific Power Co. An inventory of the agricultural accounts in Carson Valley was completed to determine (1) the horsepower of the pump and (2) whether it was used for ground-water pumpage or, instead, for lift from a ditch or pond. Pump-efficiency tests were conducted at 14 sites by Sierra Pacific and U.S. Geological Survey personnel to determine relations between acre-feet of water pumped and kilowatt-hours of power consumed. These data were then applied to other pumps of similar horsepower and pumping lifts, to estimate total agricultural pumpage for 1981-83.

TABLE 10.--*Simulated quarterly and annual water budgets for water years 1981-83*

[Acre-feet]

Component	Quarter[1] 1	2	3	4	Annual total (rounded)
			Water Year 1981		
INFLOW					
West Fork Carson River	4,300	6,700	28,100	4,300	43,400
East Fork Carson River	15,100	22,000	93,200	12,800	143,100
Runoff from perennial and ephemeral drainages	3,900	4,000	4,300	3,300	16,000
Precipitation[2]	5,200	11,000	4,200	300	21,000
Subsurface inflow[3]	8,100	8,000	8,200	7,000	31,000
Total (rounded)	37,000	52,000	138,000	28,000	255,000
OUTFLOW					
Mainstem Carson River	26,100	39,000	70,300	1,300	136,700
Pumpage	1,200	900	3,900	8,500	14,500
Evapotranspiration	12,000	2,900	49,000	57,000	121,000
Total (rounded)	39,000	43,000	123,000	67,000	272,000
DIFFERENCE (inflow minus outflow)	-2,000	9,000	15,000	-39,000	-17,000
			Water Year 1982		
INFLOW					
West Fork Carson River	16,400	21,300	80,700	18,000	136,400
East Fork Carson River	46,800	87,000	276,900	75,300	486,000
Runoff from perennial and ephemeral drainages	4,600	3,900	8,700	7,500	25,000
Precipitation[2]	18,000	23,000	14,000	10,000	65,000
Subsurface inflow[3]	7,800	9,100	11,000	9,900	37,800
Total (rounded)	94,000	144,000	391,000	121,000	750,000
OUTFLOW					
Mainstem Carson River	66,300	132,400	320,200	66,800	585,700
Pumpage	900	600	1,800	4,100	7,400
Evapotranspiration	5,200	1,200	50,000	61,000	117,000
Total (rounded)	72,000	134,000	372,000	132,000	710,000
DIFFERENCE (inflow minus outflow)	22,000	10,000	19,000	-11,000	40,000

TABLE 10.—*Simulated quarterly and annual water budgets for water years 1981-83*—Continued

[Acre-feet]

Component	Quarter[1] 1	2	3	4	Annual total (rounded)
INFLOW			Water Year 1983		
W.F. Carson River	13,900	11,500	103,800	46,000	175,200
E.F. Carson River	57,300	69,900	351,200	137,500	615,900
Runoff from perennial and ephemeral drainages	6,200	5,800	13,000	12,000	37,000
Precipitation[2]	25,000	34,000	9,100	12,000	80,000
Subsurface inflow[3]	9,500	8,900	16,000	12,000	46,000
Total (rounded)	112,000	130,000	493,000	220,000	955,000
OUTFLOW					
Mainstem Carson River	104,700	136,200	429,000	150,500	820,400
Pumpage	1,000	1,000	1,800	3,200	7,000
Evapotranspiration	5,500	1,300	52,000	63,000	122,000
Total (rounded)	111,000	139,000	483,000	217,000	949,000
DIFFERENCE (inflow minus outflow)	1,000	-9,000	-10,000	3,000	5,000

[1] Quarters: 1, October-December; 2, January-March; 3, April-June; 4, July-September.

[2] Precipitation on phreatophytic and crop lands.

[3] Includes secondary recharge of water pumped for agriculture, and imported sewage.

TABLE 11.—*Quarterly variation in runoff at Daggett Creek and precipitation at Minden for the long term and for water years 1981-83*

	Runoff at Daggett Creek[1]					Precipitation at Minden[2]				
	Quarter[3]					Quarter[3]				
	1	2	3	4	Annual	1	2	3	4	Annual
Percentage of long-term annual average:										
	22	26	31	21	100	36	38	16	10	100
Data for calibration period, as percentage of long-term quarterly and annual averages:										
Water year 1981	82	68	61	47	65	33	65	56	7	40
Water year 1982	74	98	131	150	115	160	202	133	294	200
Water year 1983	129	92	240	210	170	114	141	180	238	170

[1] Period of record, water years 1964-83.
[2] Period of record, water years 1906-83.
[3] Quarters: 1, October-December; 2, January-March; 3, April-June; 4, July-September.

Ground water used for agricultural purposes is generally pumped directly into irrigation ditches and then diverted to individual fields. Some of the pumped water returns to the ditch system, but it generally is diverted again for flood irrigation farther downstream. The amount of unconsumed ground-water pumpage that leaves the valley in the Carson River is probably small, especially during dry years when most of the pumpage takes place and the water table is depressed.

Data on municipal pumpage in Minden and Gardnerville were obtained from kilowatt-hour information and pump-efficiency tests. Sporadic flow-meter records were also used as a check on computed pumpage. Information on ground-water use by Gardnerville Ranchos and the U.S. Lahonton Fish Hatchery was obtained from flow-meter records. Water from the fish hatchery is returned directly to the East Fork of the Carson River.

Secondary recharge of municipal pumpage is discussed in a later paragraph on sewage.

Domestic pumpage was estimated from (1) house counts compiled by the Douglas County Planning Commission from 1979 aerial photography and (2) household use rates calculated from data supplied by the Indian Hills Water Supply Co. (written and oral communications, 1984). The average use rate is about 0.4 acre-ft/yr per household, with summer rates equivalent to about 0.9 acre-ft/yr and winter use equivalent to about 0.2 acre-ft/yr. Some of the water pumped for domestic use is not consumed, and instead returns to the aquifer through percolation from septic-tank drain fields and lawns; this is referred to as secondary recharge. In most of the areas in Carson Valley where septic tanks are in use--such as Johnson Lane, the Gardnerville Ranchos, and the western alluvial fans--depth to water approaches 100 feet. Infiltration rates depend on unsaturated hydraulic conductivity and soil-moisture content, which are difficult to measure or estimate. Compared to evapotranspiration and agricultural pumpage, however, domestic pumpage is minor in magnitude; as a result, secondary recharge from domestic pumpage has not been evaluated quantitatively.

Municipal sewage generated within the valley is processed and placed into ponds at the Minden-Gardnerville plant near the intersection of U.S. Highway 395 and Muller Lane and at the Indian Hills plant approximately 1.5 miles south of the Indian Hills Subdivision. Monthly records from each plant were used to estimate recharge by infiltration from the sewage ponds. Twenty-five percent of the sewage is assumed to be lost to evaporation from pond surfaces, and the remainder infiltrated to the water table as secondary recharge. The total volume of sewage generated within Carson Valley and available for recharge was estimated at about 1,000 acre-ft/yr for 1981-83.

Imported sewage from the Lake Tahoe basin is used for crop irrigation in three areas of the valley. At the Settlemeyer Ranch, effluent from the Round Hill area is applied by sprinkler in winter months and by ditches during summer months. At the Schneider Ranch, sewage from Incline Village is applied by sprinkler from April to October; during winter months, the sewage is piped to the Carson River. The South Lake Tahoe Public Utility District exports sewage to Indian Creek Reservoir south of Carson Valley, from which it is transported north to the valley by way of Snowshoe Thompson ditch, for irrigation. Total sewage imported to the valley during 1981-83 was estimated at about 5,000 acre-ft/yr. Recharge from imported sewage was assumed to be 75 percent of the actual imported volume, due to evaporation and runoff losses during application.

The seasonal distribution of evapotranspiration was obtained from Pennington (1980, p. 46), who showed that 9 percent occurred in quarter 1 (Oct.-Dec.), 2 percent in quarter 2 (Jan.-March), 40 percent in quarter 3 (April-June), and 49 percent in quarter 4 (July-Sept.). See figure 11 for monthly distribution.

Transient Calibration for Water Years 1981-83

In transient simulations for 1981-83, the water years were divided into quarters and, as discussed previously, quarterly rates were calculated for each water-budget element. The result was 12 quarterly stress periods, between October 1980 and September 1983. The head distribution obtained from the steady-state calibration was used for initial-head values.

The distributions of horizontal and vertical conductivity were adjusted until acceptable agreement between observed and simulated head was obtained for both steady-state and transient simulations. The simulated heads were not sensitive to values of specific yield and storage coefficient (see section on model sensitivity). These values required adjustment beyond that considered to be geologically reasonable to achieve a significant change in simulated head. For this reason, initial estimates of storage terms were considered adequate for the transient calibration.

The adjustment of streambed conductance was a matter of trial and error, with one basic guideline: because conductance is a function of streambed area (including flooded fields), it should increase during summer months when flood irrigation greatly increases the wetted area, and decrease during winter months when surface-water flows are confined to the ditch and stream channels. Table 12 shows the variation in streambed conductances used in the final calibrated model. The guideline proved to be generally applicable: the first and second quarters (winter months) required smaller conductances and the third and fourth quarters (summer months) required larger conductances than those used in the steady-state simulation. Winter quarters having below-normal runoff (see table 11) required conductances that were considerably less than the steady-state values. Quarter 3 of 1981 (spring and early summer) required a very large conductance, probably due to the early and frequent flood irrigation that resulted when ranchers took advantage of spring snowmelt runoff while the supply lasted. In all years, the same conductance was applicable for quarter 4 (fall months).

Figure 16 shows simulated versus observed average quarterly flows of the Carson River at the gage near Carson City. Simulated flows match observed flows within an average of 20 percent.

Figure 17B shows histograms of the difference between simulated and observed heads for each quarter. In most instances for layer one, the differences are between plus and minus 20 feet, and for layer two, between plus and minus 10 feet. This large range is attributed mostly to the fact that the simulated head applies to the center of each node, whereas the observed head is taken from individual wells that are generally not centrally located in the grid cell. This effect is greatest around the edge of the valley, where hydraulic gradients are the steepest. Also, many wells are affected by surface-water sources at varying distances, and by nearby pumping, whereas in the model these effects are averaged for the entire square-mile cell.

TABLE 12.—*Streambed conductance used in calibrated model*

[Feet per second]

	East-side ditch systems	Valley floor
Steady-state simulations	1.2	2.0
Transient simulations:		
	Water Year 1981	
First quarter	0.05	0.2
Second quarter	.05	.2
Third quarter	5.0	20
Fourth quarter	.9	3.5
	Water Year 1982	
First quarter	0.2	0.7
Second quarter	.4	1.5
Third quarter	1.3	5.0
Fourth quarter	.9	3.5
	Water Year 1983	
First quarter	0.4	1.5
Second quarter	.4	1.5
Third quarter	1.3	5.0
Fourth quarter	.9	3.5
	Water Year 1975	
First quarter	0.05	0.2
Second quarter	.05	.2
Third quarter	5.0	20
Fourth quarter	.9	3.5
	Water Year 1976	
First quarter	0.2	0.7
Second quarter	.4	1.5
Third quarter	1.3	5.0
Fourth quarter	.9	3.5

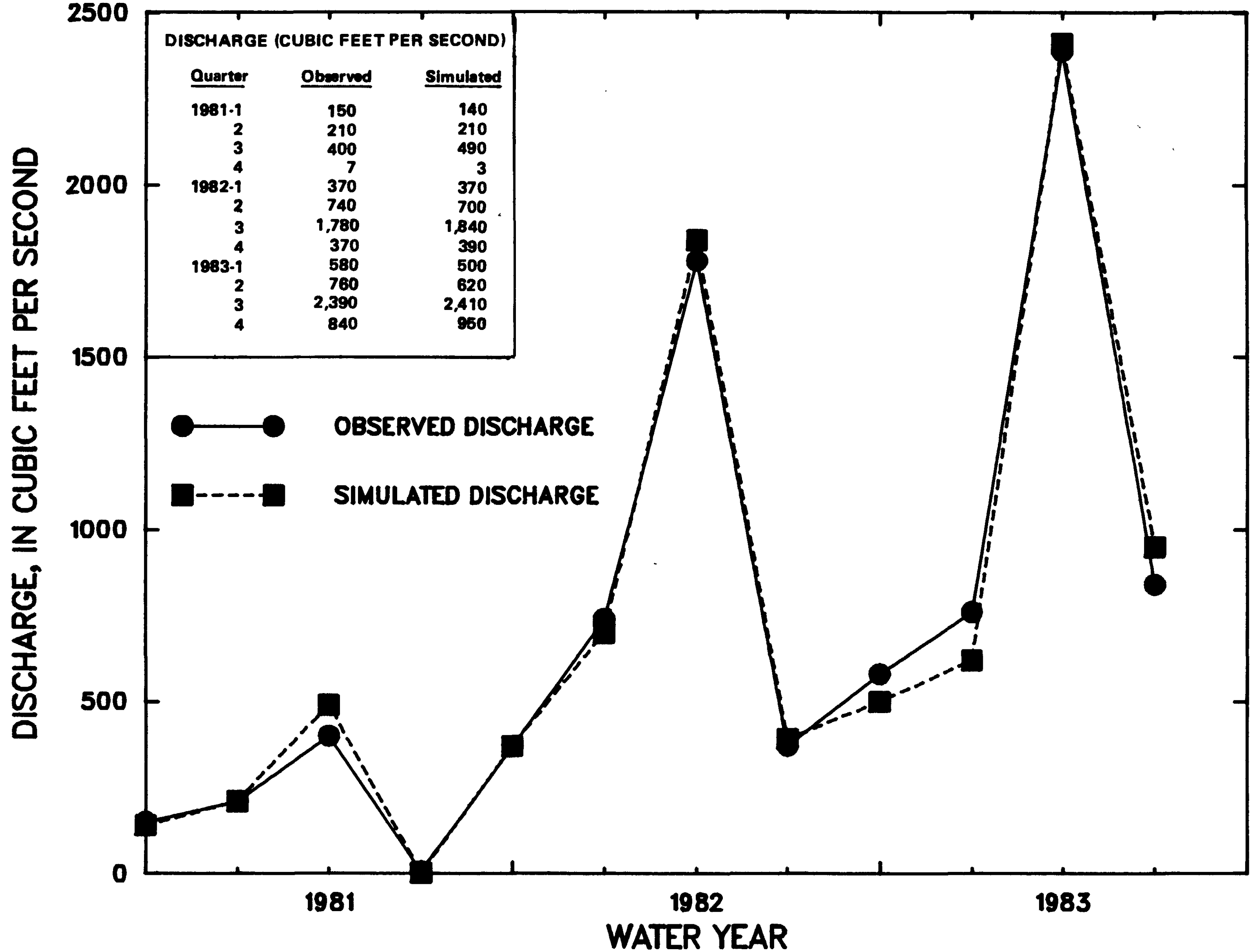


FIGURE 16.--Comparison between observed and simulated quarterly outflow of Carson River at gage near Carson City, water years 1981-83.

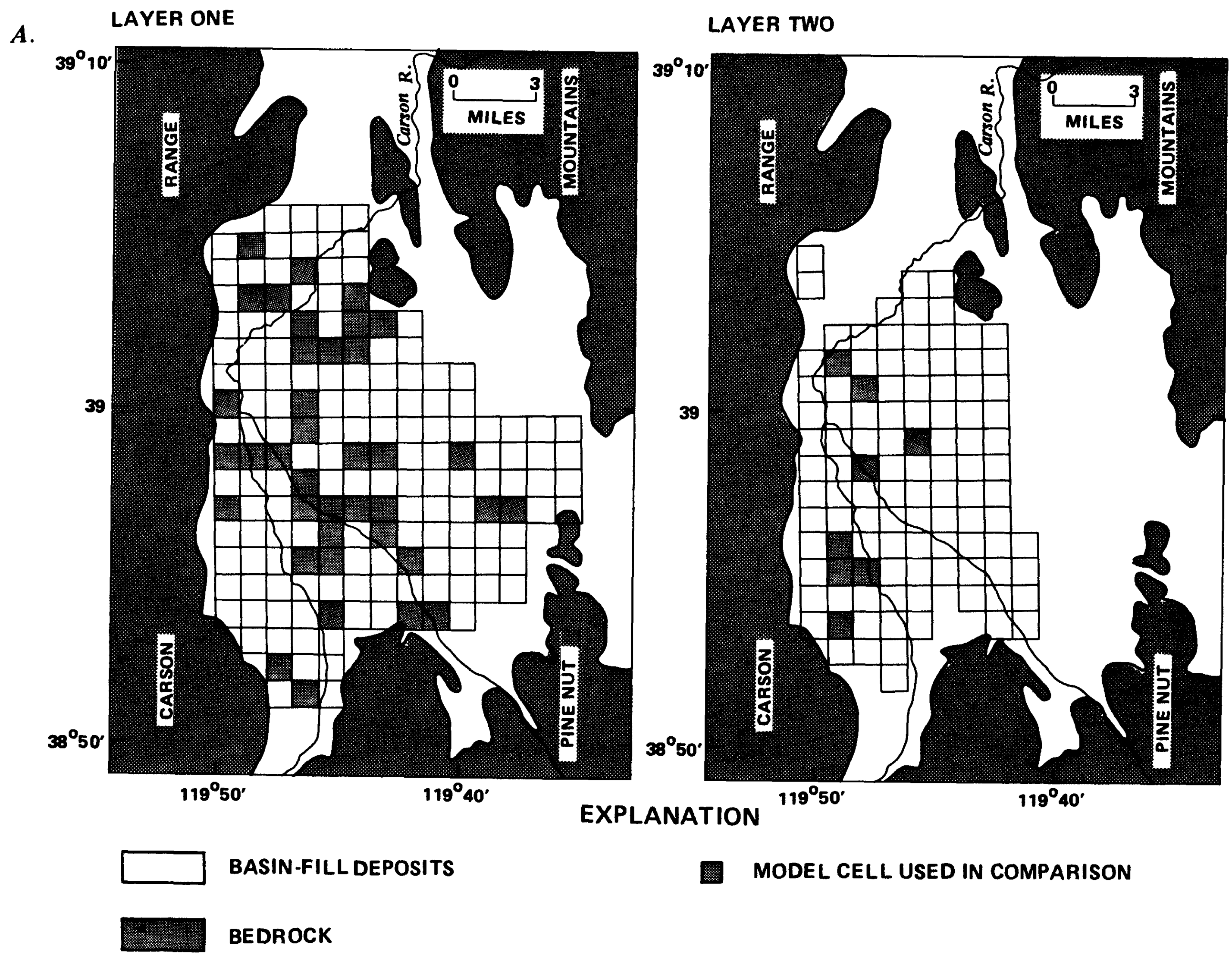


FIGURE 17.--Comparison between observed and simulated ground-water levels in model layers one and two for 1981-83, during transient calibration. *A*. Cells used in comparison (selected on basis of adequate control provided by observation-well data). *B*. Difference between observed and simulated water levels, by quarter. Negative value indicates observed head greater than simulated head.

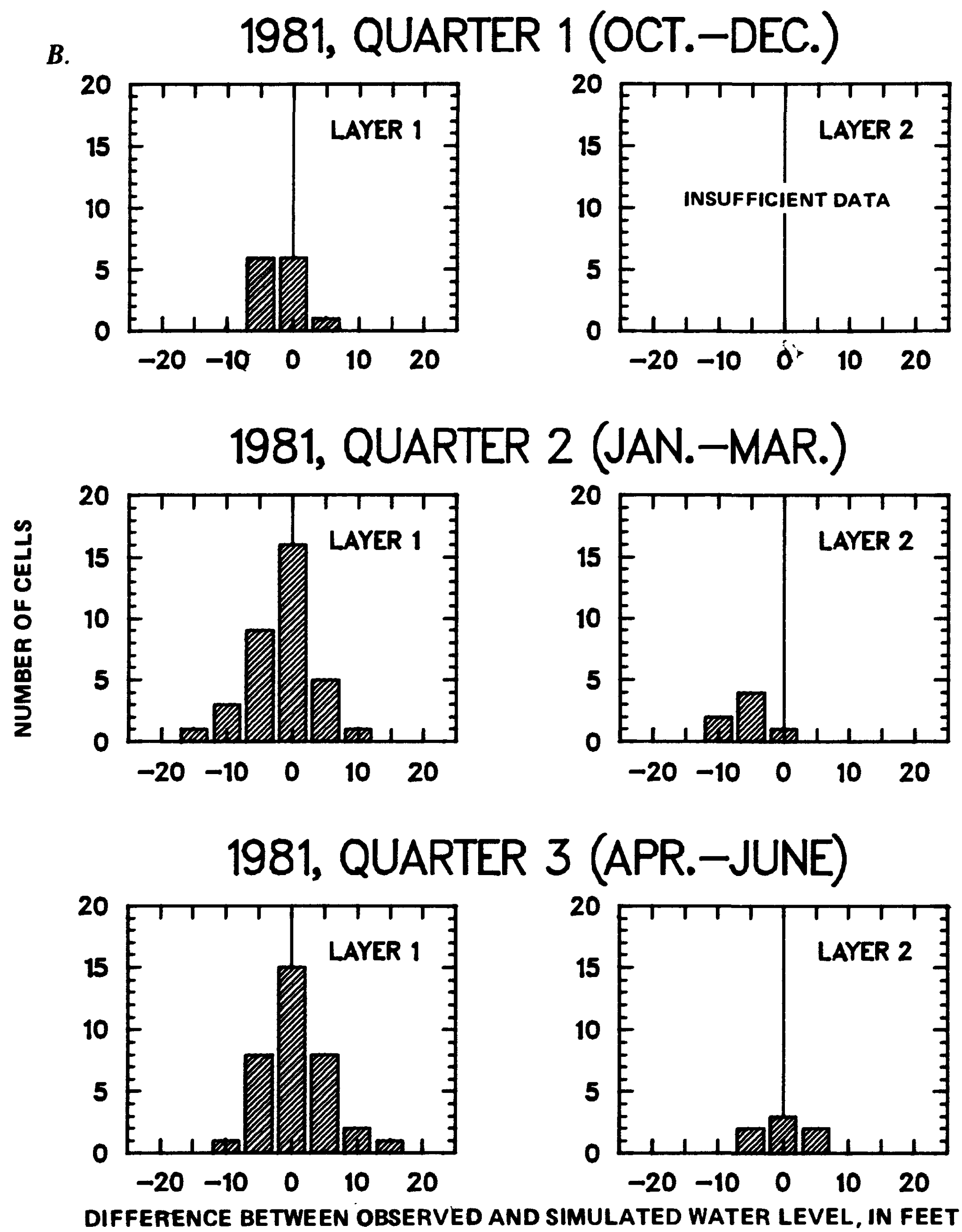


FIGURE 17.--Continued.

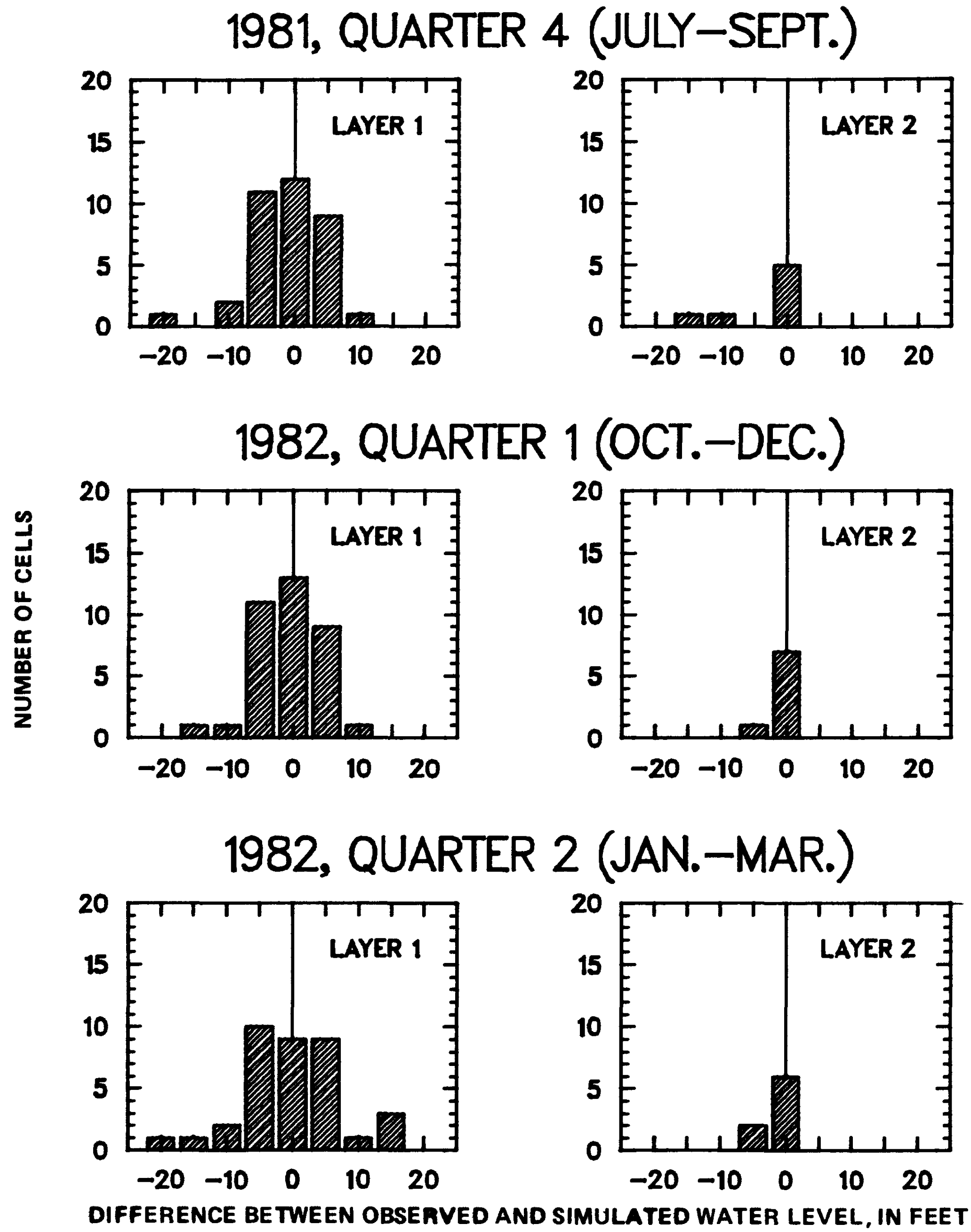


FIGURE 17.--Continued.

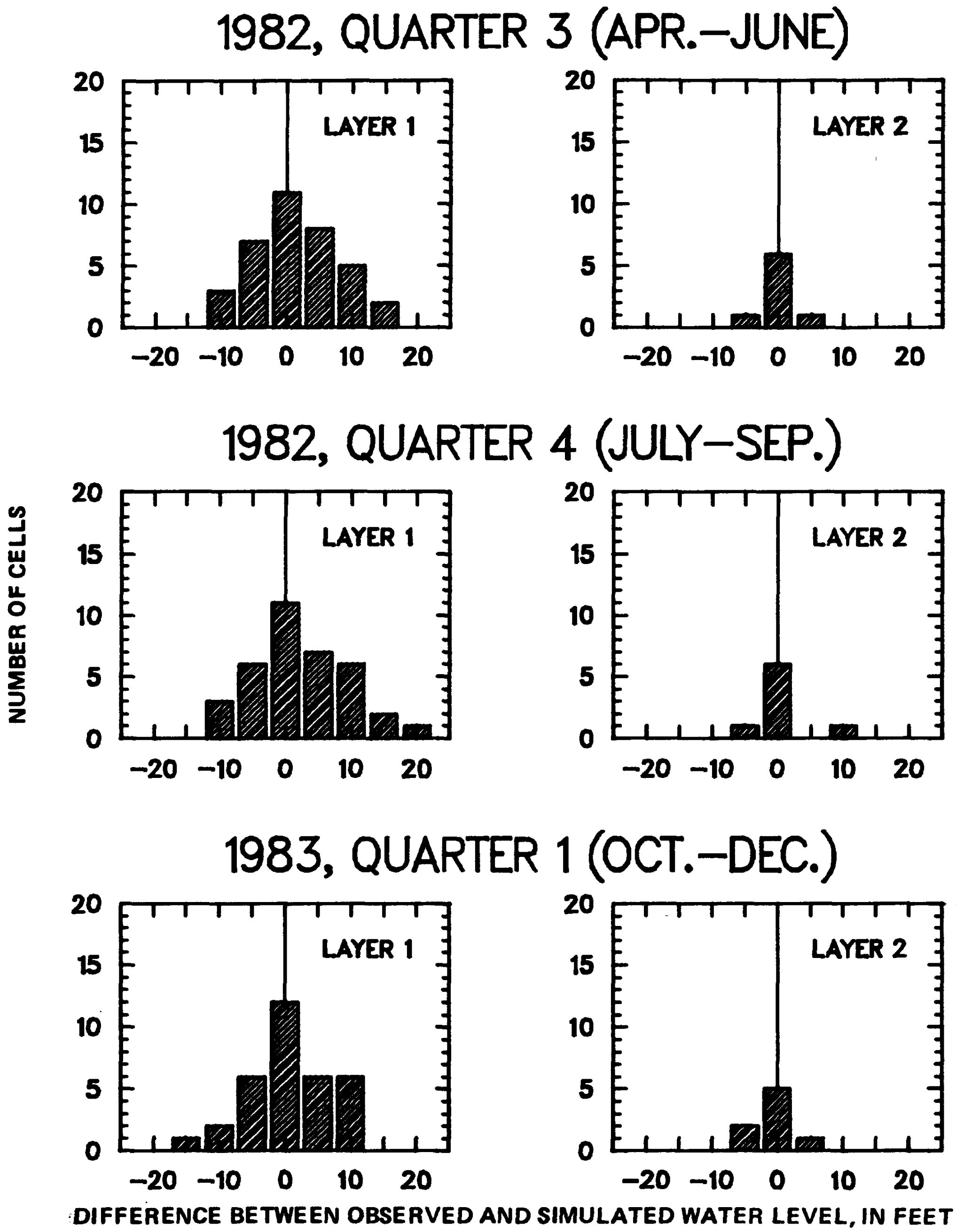


FIGURE 17.--Continued.

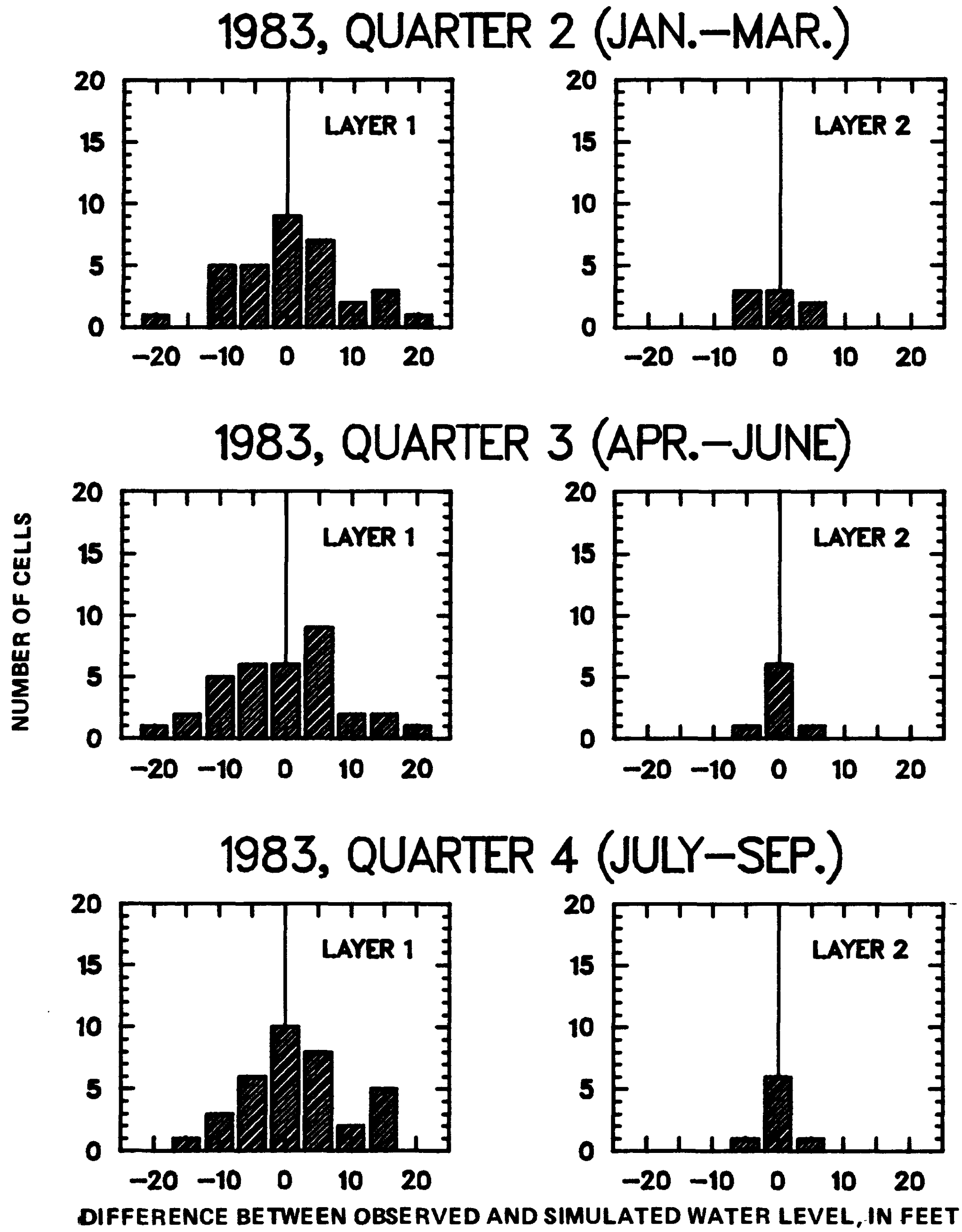


FIGURE 17.—Continued.

Figure 18 shows hydrographs of observed versus simulated heads for selected wells in the valley. In most hydrographs, the observed trend approximates the simulated heads derived from the model. Again, observation wells affected by nearby pumping and surface-water bodies, and wells located away from the center of the cell, probably cause offset of the two curves and some of the perturbations in the trends. For example, hydrographs of simulated versus observed water-level fluctuations for the Allerman well (Well 12, figure 18) coincide precisely when irrigation is not simulated in that cell. This may be because the well is upgradient from the ditch system on an alluvial fan and is not actually affected by irrigation infiltration. However, in the model, the grid cell containing the Allerman well extends onto the valley floor and also contains a major ditch. This shows the effects of the large grid scale used in the model. To correct discrepancies such as these would require a grid system with a smaller cell size.

Figure 19 shows the distribution of simulated and observed drawdown at the end of quarter 4 in 1981 (July-Sept.). Although not an exact fit, observed and simulated values fall generally in the same range in all areas of the valley. The pumping of some observation wells in 1981 could account for some of the discrepancies.

As an independent check of the numerical model, the overall magnitude of decrease in storage associated with the observed water-level declines in the unconfined (water-table) aquifer was calculated for quarter 4 of 1981. The total change was estimated to be about 38,000 acre-ft. Similarly, hydraulic-head changes in the confined aquifer were calculated: due to the small storage coefficient, the calculated decrease in storage was only about 200 acre-ft. The change in water levels for other stress periods was not considered sufficient to obtain an accurate measure of the change in ground-water storage.

The calculated decline in storage from the water budget for quarter 4 of 1981 is about 39,000 acre-ft (table 10). The close match between that value and the one calculated above is probably fortuitous, given the errors involved in the estimations, but it nonetheless shows a good match between observed and simulated changes in storage.

The simulated water budget (table 10) also indicates that abundant runoff during the winter and spring of 1982 resulted in a large increase in ground-water storage in quarter 3 (April-June); storage depletion for quarter 4 of 1982 was much less than in quarter 4 of 1981. Quarter 2 in 1983 (Jan.-March) also showed a storage depletion. This could indicate that recharge was somewhat underestimated for those months, because most well hydrographs showed rising water levels at that time. The lack of storage depletion during the fall of 1983 showed that the ground-water reservoir was probably filled to capacity after water years 1982-83.

Inspection of the cell-by-cell budget for the transient calibration period 1981-83 indicates that, during winter months, the stream system was gaining as a whole, fed by drainage from the ground-water system plus any excess precipitation runoff. During summer months, the stream system lost flow to evapotranspiration and percolation to the water-table aquifer.

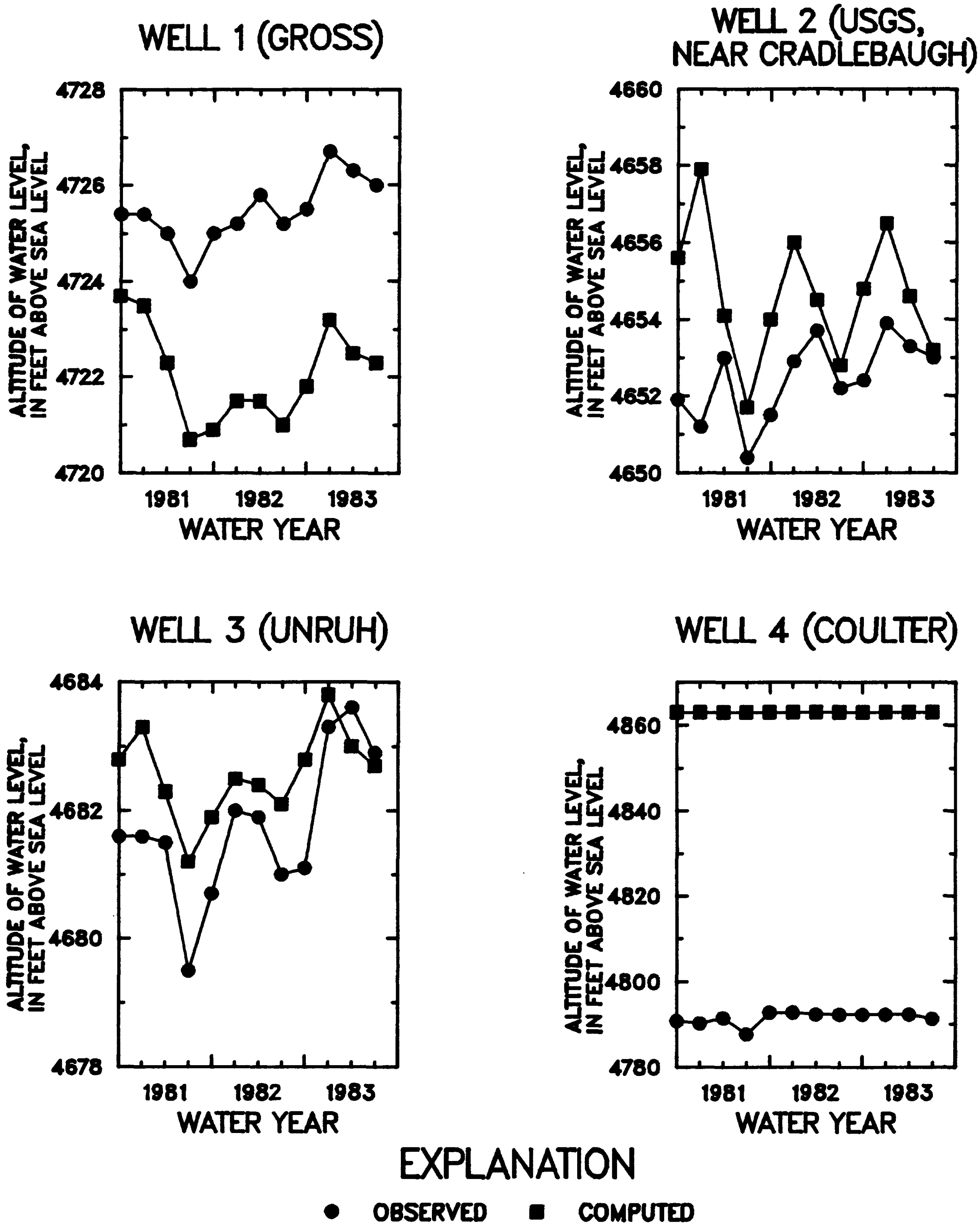


FIGURE 18.--Comparison between observed and simulated water-level fluctuations at selected wells, 1981-83. Well locations are shown in figure 5.

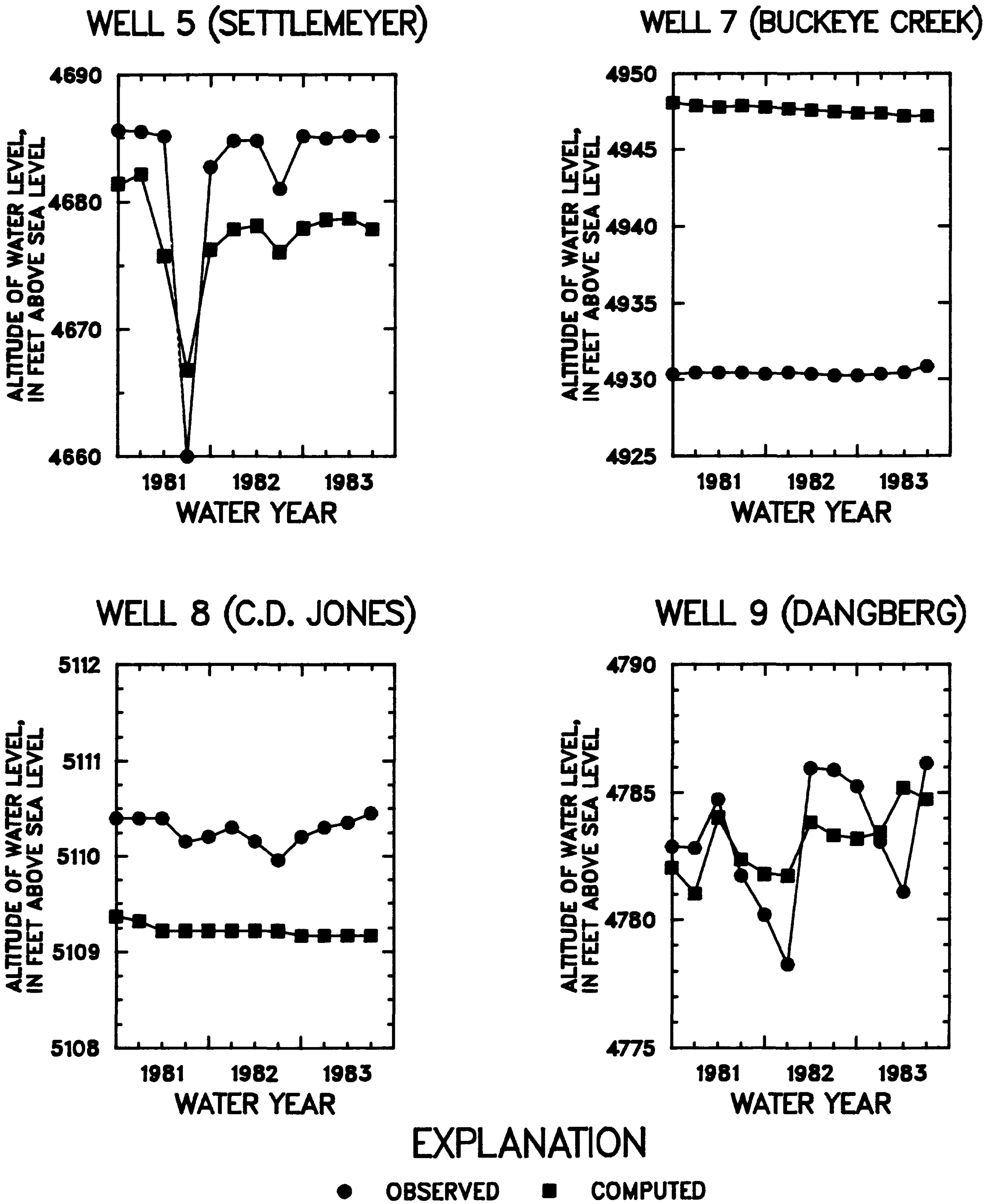


FIGURE 18.--Continued.

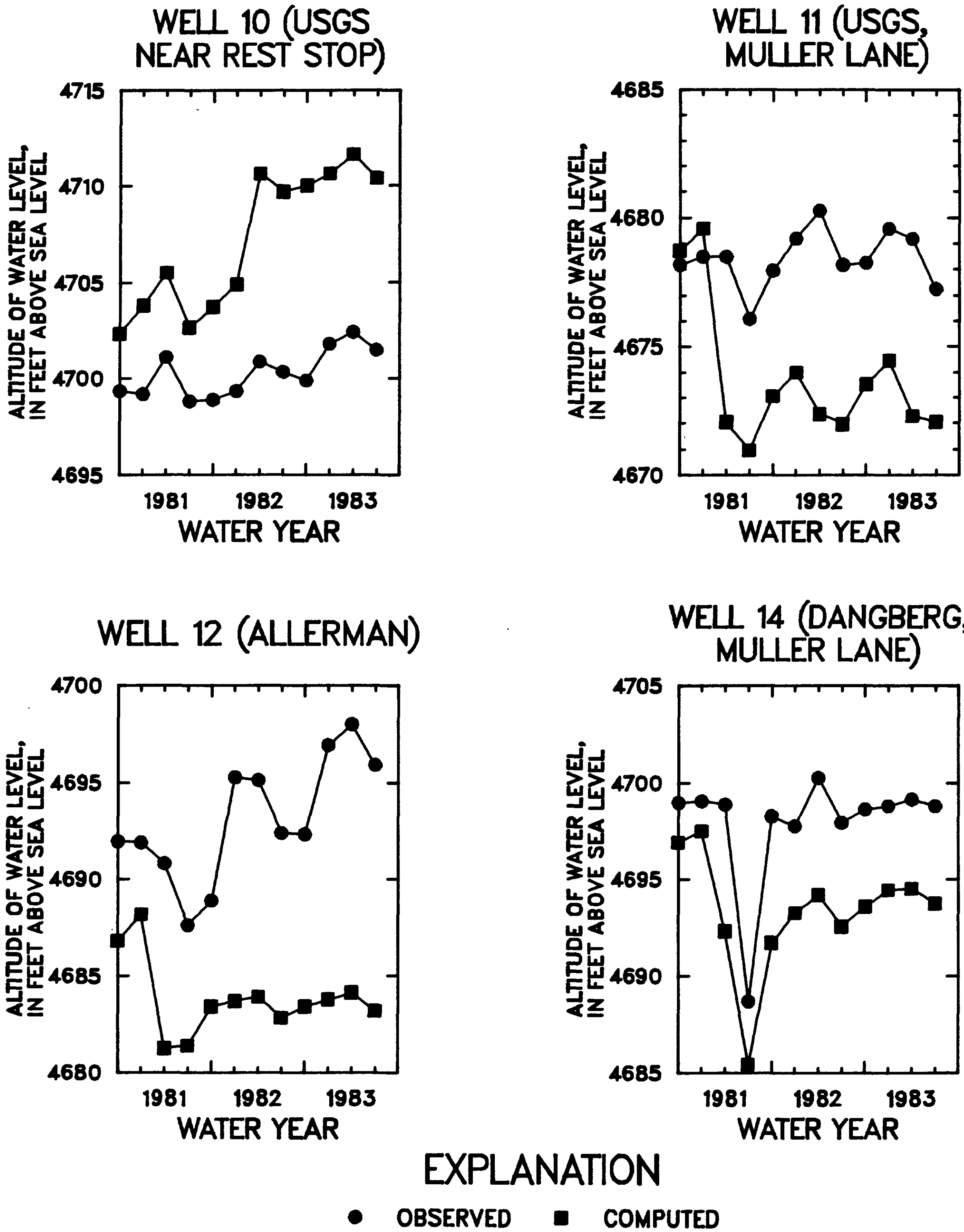


FIGURE 18.--Continued.

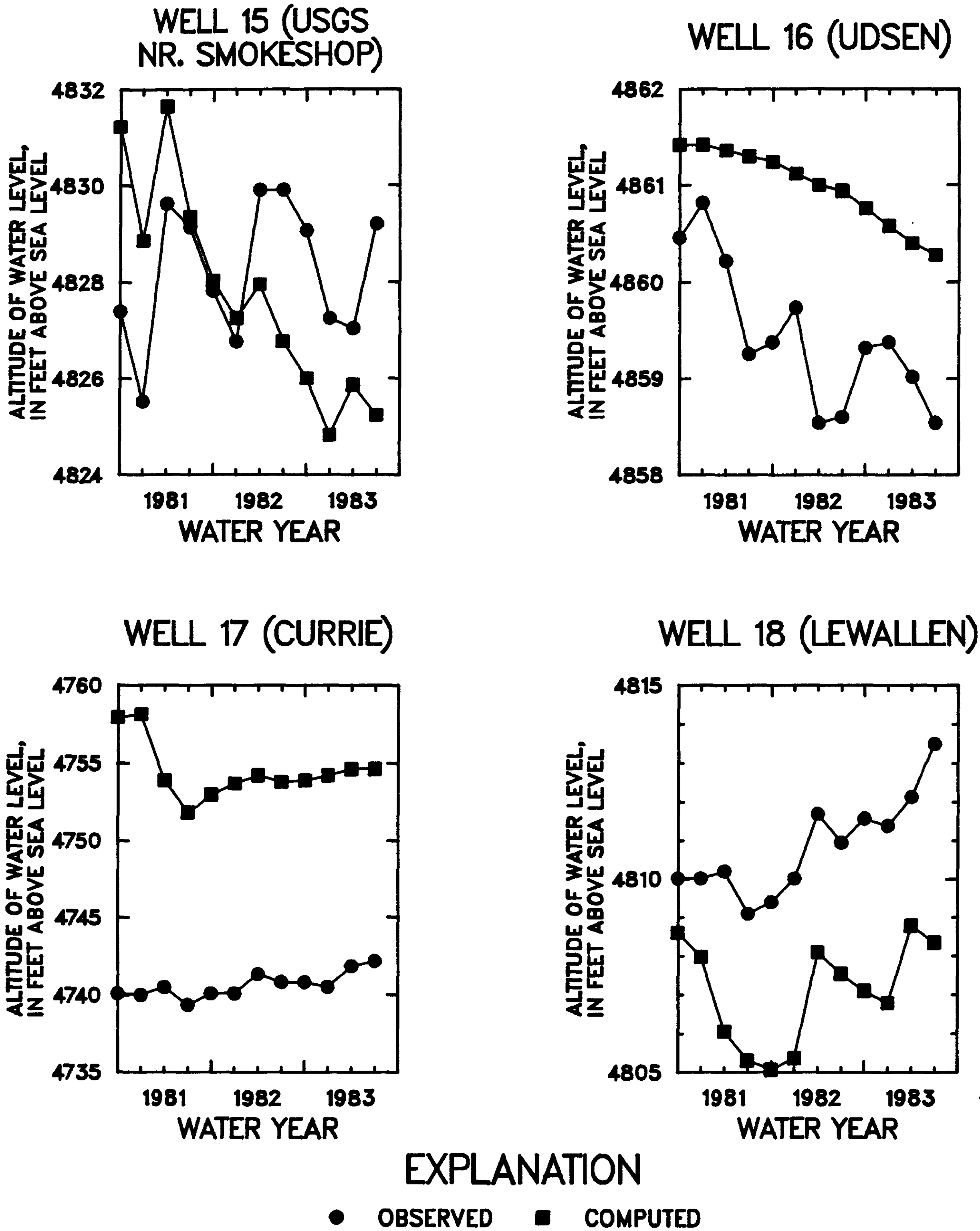


FIGURE 18.--Continued.

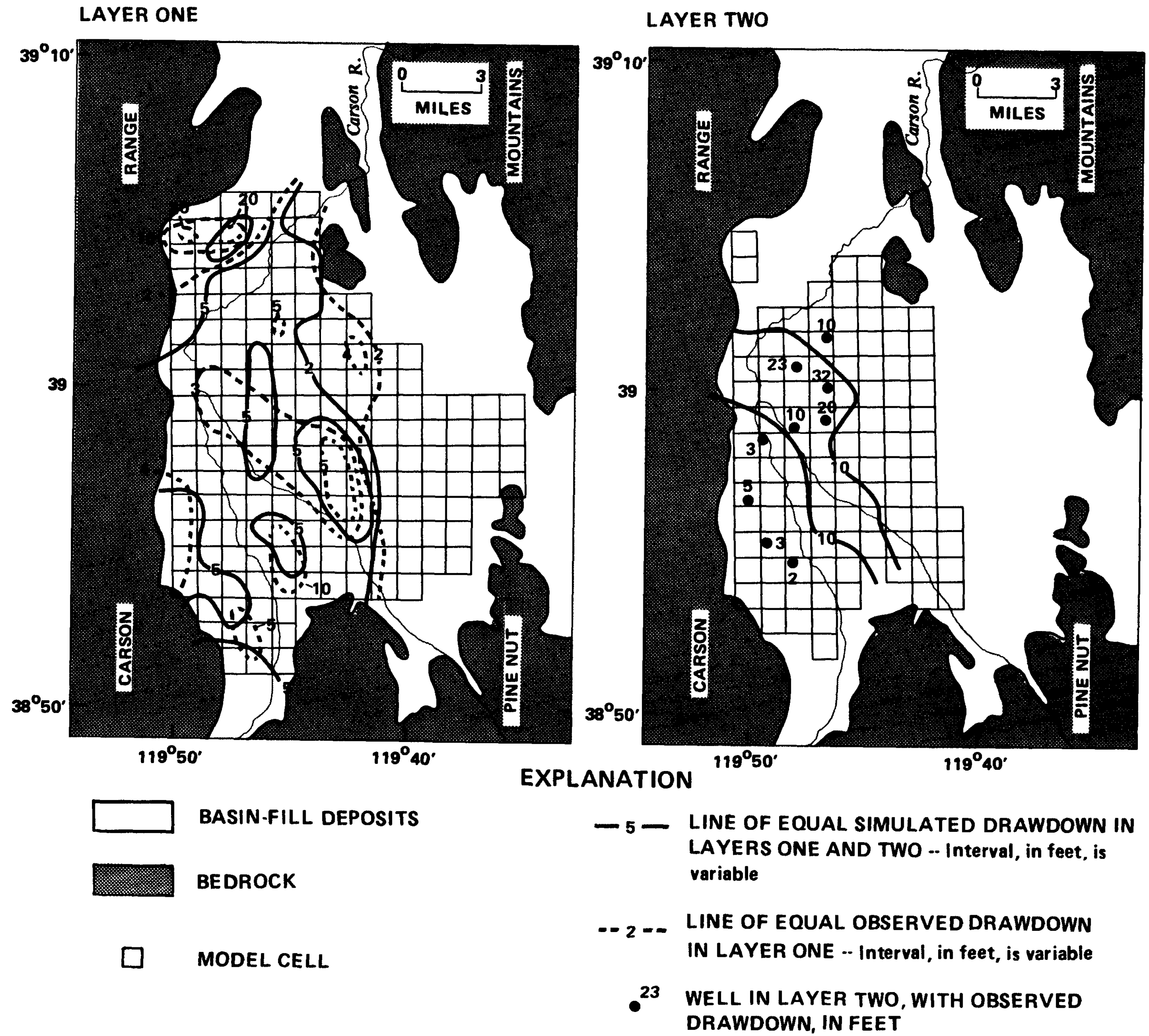


FIGURE 19.--Comparison between observed and simulated drawdown in layers one and two during quarter 4, 1981 (July-Sept.).

Cell-by-cell flow budgets also indicate that upward leakage from layer two was almost constant throughout the year, averaging about 4,400 acre-ft per quarter. Thus, the simulation confirms that upward flow from layer two to layer one was a constant source of recharge to the unconfined aquifer; this concept is supported also by water-level fluctuations (see section "Water-Level Fluctuations," and figure 5B, wells 9 and 15).

Figures 16 through 19 show that the calibrations simulations approximate the observed changes in water levels, ground-water storage, and streamflow during the 3-year stress period. To verify the applicability of the model as a predictive tool for surface-water flows and water levels during years outside the calibration period, model simulations were made for 1975, a wet year, and 1976, a dry year. Recharge was calculated using the same methods as described for the transient calibration, and using the streambed conductances from 1982 and 1981, respectively. Figure 20 shows observed versus simulated flows of the Carson River at the gage near Carson City. Here, the match is not as good as for the period 1981-83. The trends, however, are quite similar, allowing more confidence to be placed on simulated Carson River flow volumes during predictive runs. Because no water-level data were collected during 1975 and 1976, the accuracy of the simulated water levels cannot be assessed; however, they appear reasonable when compared to water levels for the wet and dry years observed during the calibration period 1981-83.

Model Sensitivity

A sensitivity analysis of the model allows evaluation of the relative importance of various model elements and the methods that were used to estimate them. The model elements used for sensitivity simulations were conductivity of layers one and two, vertical conductivity of the confining layer, specific yield of layer one, storage coefficient of layer two, streambed conductance, recharge and evapotranspiration rates, and thickness of layer two. Sensitivity simulations were conducted over the 3-year calibration period.

Sensitivity simulations show that the hydraulic conductivity of layer one and the recharge rates at the model boundary are the most sensitive model elements with respect to simulated heads, especially on the east side of the valley, in the Jacks Valley area, and along the alluvial fans on the extreme west side of the valley. Increasing these elements by a factor of two and decreasing them by half causes changes in simulated heads on the order of tens of feet at the margins of the valley floor; however, on the valley floor, head changes were less than 1 foot. The same magnitude of change in the hydraulic conductivity of layer two, vertical hydraulic conductivity, specific yield of layer one, streambed conductance, and evapotranspiration rates causes changes in simulated heads of less than 10 feet. Changing the storage coefficient of layer two by plus or minus a factor of 10 causes changes in simulated heads of less than 1 foot.

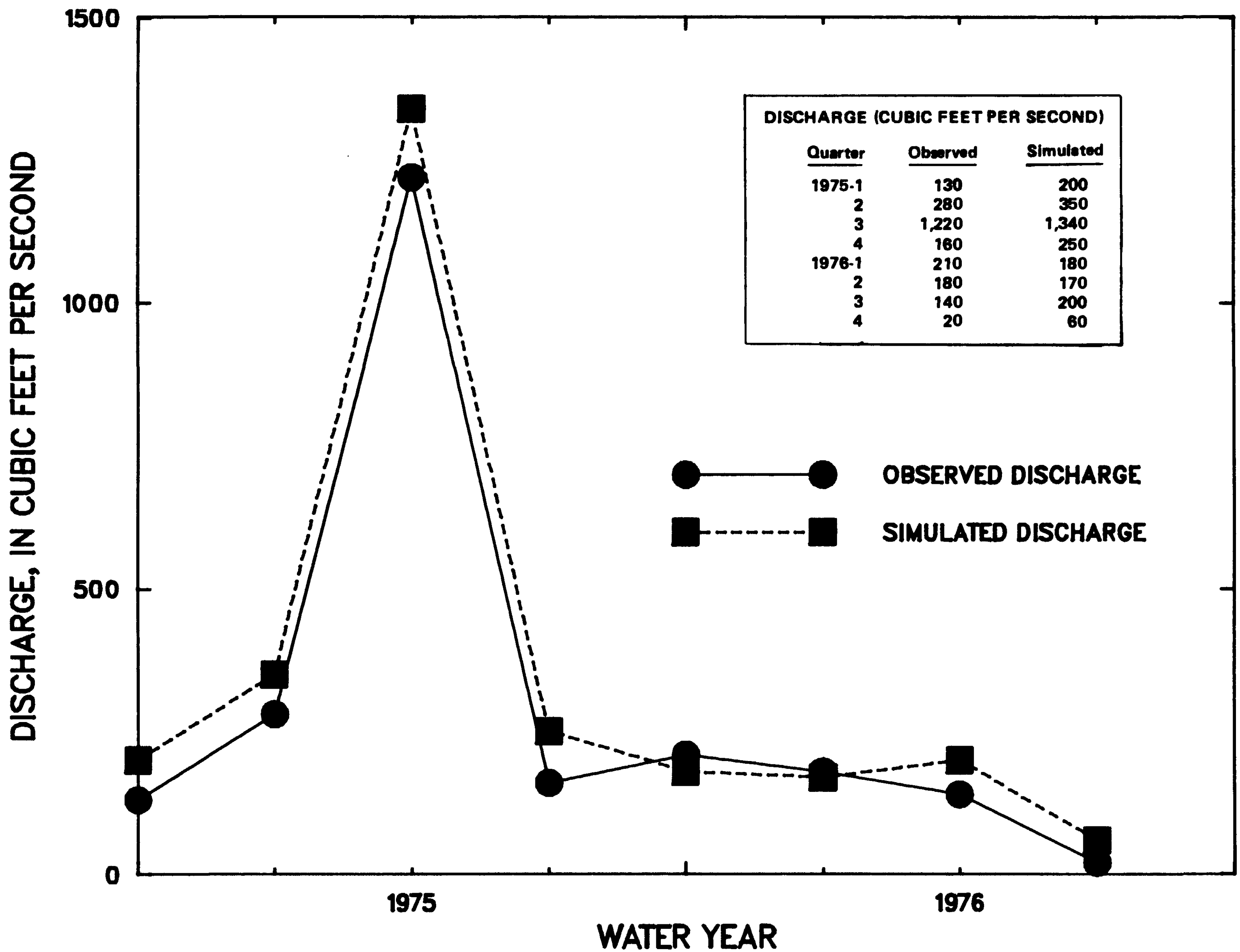


FIGURE 20.--Comparison between observed and simulated quarterly outflow of Carson River at gage near Carson City, water years 1975-76.

To determine the potential effect of a large section of Tertiary sediments underlying the basin-fill deposits on the west side of the valley, the thickness of layer two in that area was decreased by 1,000 feet, thereby simulating a section of Tertiary sediments 1,000 feet thick with zero hydraulic conductivity. The decrease in thickness also simulates an increase in consolidation or a decrease in grain size that might be present in the Quaternary deposits. The change in thickness causes a change of about 5 feet in simulated heads for layer two, and less than 1 foot for layer one.

The effect of varying model elements on Carson River outflow from the valley was relatively small. Doubling recharge and evapotranspiration rates had the greatest effect, changing river outflow by about 12 percent at the end of the 3-year period. Doubling conductivity of layer one and streambed conductance caused about a 6-percent change in river outflows, and the remaining elements caused less than a 5-percent change.

Model Limitations

The model was calibrated using data collected from 1981, a dry year, through 1983, a wet year. Although pumpage is at a maximum in dry years when surface water cannot supply the demand for irrigation water, pumped water was still a minor element in the water budget for the calibration period. Initial estimates of storage terms were adequate for an acceptable transient calibration. High pumping rates might require adjustment of these values to obtain an acceptable calibration. For this reason, and because of the relatively short calibration period, the model should be considered preliminary until continued ground-water development does stress the system sufficiently to provide a more rigorous test. Also, model estimates of water-level changes and Carson River outflows must be considered only as indications of long-term trends, and not as exact values.

The square-mile node size of the model presents some problems, especially on the west side of the valley where nodes cover areas of differing land use and hydrogeology. The east parts of these nodes cover the valley floor and the incorporated irrigation system, whereas the west parts cover steep alluvial fans that do not receive recharge from the irrigation system. Predicted drawdowns in these areas might be too small, depending on where pumpage actually takes place. Pumping high on the alluvial fans would cause greater drawdowns than on the valley floor, because subsurface recharge would be captured. On the valley floor, drawdowns would be less, because streamflow is the ultimate source of most of the pumped water there.

Another problem is the Jacks Valley-Indian Hills area, where the areal distribution of hydraulic conductivity is very sensitive, probably due to the mix of aquifer materials and the large range in aquifer thickness in the area. Water levels were measured in the only available observation wells, which are pumped occasionally and show a large response to pumping.

This is consistent with the model results; however, due to the lack of unpumped observation wells, the determination of how widespread the drawdown actually is and what magnitude of storage depletion may have taken place is difficult.

The assumptions of a constant flux and a no-flow boundary for the model could cause somewhat greater drawdowns near the boundaries in the modeled area than would actually occur. This is due to the possible dewatering of bedrock materials, which would provide an alternate source of water when pumping is heavy and drawdowns are large in the adjacent basin-fill aquifers.

Simulations of Possible Future Ground-Water Development

The Douglas County Planning Commission has indicated several geographic areas of interest in Carson Valley where simulations would be useful in evaluating the impact of development on surface- and ground-water resources. The simulations involve pumping of ground water and, in some instances, changes in diversions and ditch flows that would accompany urban development.

Secondary recharge of pumped water is not considered in these simulations because often, under heavy development, pumped water will be partly reclaimed as sewage effluent and recharge will be gained wherever the sewage is discharged. In areas where septic tanks and drain fields are employed, as discussed previously, recharge is dependent on the depth to water and is difficult to estimate accurately. The percolation from lawn watering involves the same problems. To simplify the predictive simulations, secondary recharge of pumped water is ignored; thus, drawdowns and changes in storage and Carson River outflow represent a worst-case scenario.

Any change in the volume of water imported to Carson Valley is not considered in the simulations. This omission also will cause overestimation of drawdowns and changes in river outflow if import volumes significantly exceed the 1983 amounts. The magnitude of overestimation depends on the volume of imported water, the location of its application, and the nature of its disposition (such as evaporation or infiltration ponds as opposed to irrigation).

A stress period of 1 year is used, along with long-term average recharge, streamflow diversion, and evapotranspiration rates. Heads obtained from the steady-state calibration are used as the initial water levels. For all scenarios, after 45 years of simulated pumping, head changes are less than 1 ft/yr and the hydrologic system is essentially in equilibrium. After the 45-year stress period, pumping is stopped and the system is allowed to recover for 45 years.

Figures 21 through 26 show the change in Carson River outflow, net river leakage, evapotranspiration, storage, and water-level drawdown for each development scenario, compared to those obtained in a simulation where no pumpage occurs for the entire 90-year period. Under any annual pumpage rate, no matter how small, a decrease in storage, a water-level drawdown, and a decrease in outflow of the Carson River would be calculated. Thus, the simulated changes should be considered a worst-case scenario, showing somewhat more adverse pumping effects than would be seen in the actual hydrologic system.

In all of the simulations, the average of valley-wide pumpage measured in 1981-83 water years, about 8,000 acre-ft/yr, is used to simulate the amount of existing pumpage to which the new pumpage in areas of possible development would be added. The new pumpage is divided equally between layers one and two for all simulations.

East Side of Valley

The first three development scenarios involve two areas of potential development on the east side of the valley, proposed by the Douglas County Planning Commission. One is in the vicinity of Buckeye, about 2 miles northeast of Gardnerville, and the other is in the vicinity of Johnson Lane. About 12,000 acre-ft/yr of new pumpage is applied in the Buckeye area and about 5,000 acre-ft/yr in the Johnson Lane area. The first simulation is made by applying the Buckeye pumpage only, and the second by applying the pumpage at both Buckeye and Johnson Lane.

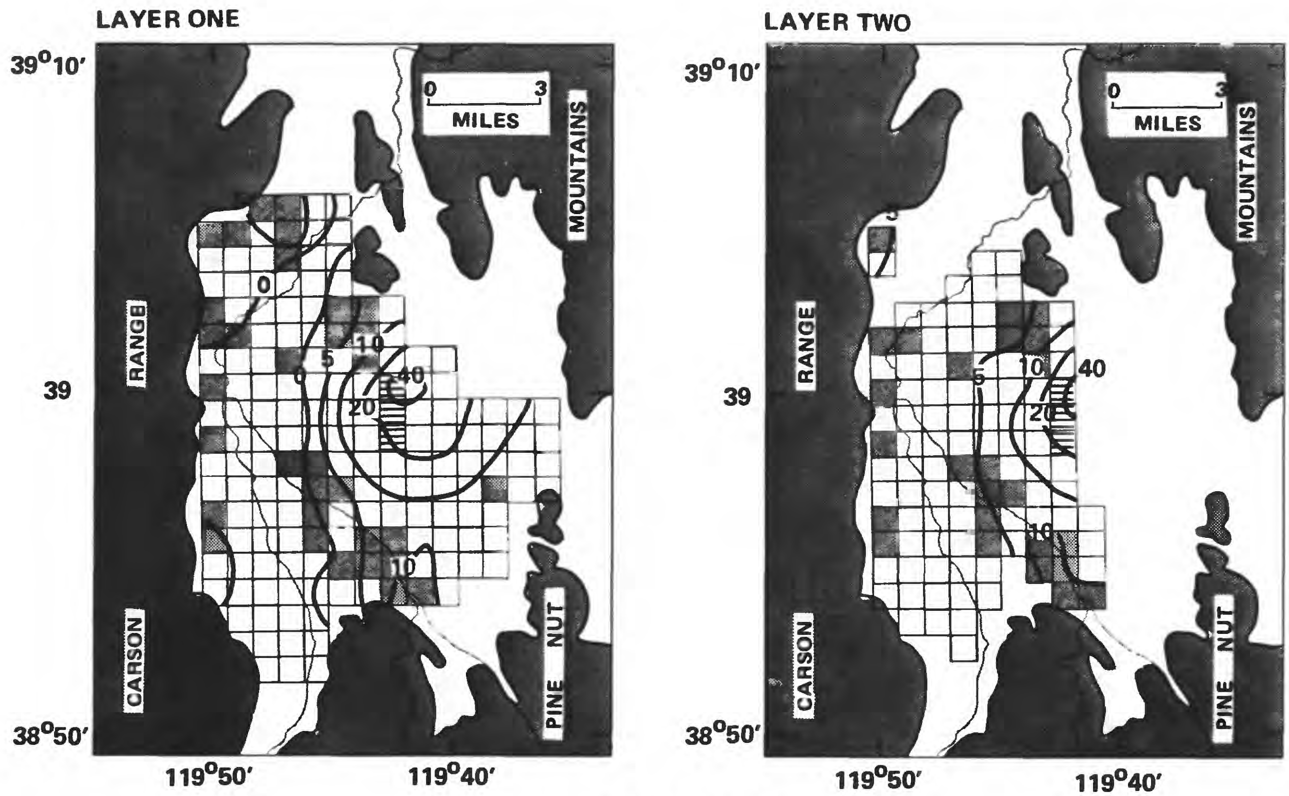
After 45 years of pumpage in the Buckeye area, water-level drawdowns in layer one reach about 40 feet in the area of heavy pumping, and about 5 and 10 feet, respectively, in the Indian Hills area and where the East Fork of the Carson River enters the valley (figure 21A). Drawdowns in the latter two areas are due to the valley-wide "background" pumping (average 1981-83 rate) outside the hypothetical developed area. The effect of simulated pumping in the Buckeye area extends farther to the south and east (upgradient as far as Fish Spring Flats) than toward the valley floor. This is due to increased river leakage to augment recharge on the east side of the valley. Simulated drawdown of water levels increases the gradient toward the shallow water table from the streambed; thus, the flow volume that percolates from the irrigation is increased. In layer two, simulated drawdowns are between 1 and 5 feet over most of the valley floor, with 5- to 10-foot drawdowns on the east side of the valley. In the area of pumping, drawdowns in layer two are the same as in layer one, due to the absence of a confining layer there. Simulated mean annual flow in the Carson River decreases by about 13,000 acre-ft/yr (figure 21C). Evapotranspiration decreases by about 6,000 acre-ft/yr due to the water-table decline; about 100,000 acre-ft of water is removed from storage during the simulated 45-year period.

The second simulation adds pumpage of 5,000 acre-ft/yr in the Johnson Lane area to that in the Buckeye area; the resulting drawdown in layer one does not extend upgradient farther than it does with pumpage only in the Buckeye area, but drawdowns in the Johnson Lane area increase by about 10 feet (figure 22A). Drawdown in layer two also increases in the Johnson Lane area by about 10 to 15 feet, and 5 feet of drawdown on the valley floor spreads about 1 mile farther west than for the first simulation with pumpage only at Buckeye. Carson River flow decreases by an additional 5,000 acre-ft/yr and storage decreases by almost 140,000 acre-ft from steady-state conditions (figure 22C). Simulated losses due to evapotranspiration remain about the same because very little evapotranspiration occurs in the Johnson Lane area.

In both simulations, Carson River outflow, river leakage, and evapotranspiration rates all recover to steady-state levels less than 45 years after the cessation of pumping. Ground-water levels, and thus storage, do not quite recover in 45 years. In these and following scenarios, recovery is not complete after 45 years in part because natural recharge is gained at a rate that is slower than the applied pumpage rate. Also, storage calculated by the model is accurate to within about 1,000 acre-ft.

Initially, for both simulations, river contributions are small, as most water comes from storage at the beginning of pumping (figures 21 and 22B). At the end of the simulation, about 70 percent of the pumped water is derived from river leakage and about 20 percent from reduction in evapotranspiration, with only about 5 percent from reduction of storage.

The third development scenario relates to land-use changes associated with development in both the Buckeye and Johnson Lane areas that could cause changes in the Carson River outflow and other hydrologic parameters. To determine one potential effect of the conversion from agricultural uses to residential and commercial development, a simulation is made with pumpage at both Buckeye and Johnson Lane maintained and the diversion ditches in the area removed from the routing system. Recharge from commercial and residential use is ignored to avoid inaccurate estimation of these quantities; thus, the simulation provides a "worst-case scenario." As water levels decline following termination of local irrigation leakage, evapotranspiration rates also decrease to zero when drawdowns reach the phreatophyte-extinction depth.



EXPLANATION

BASIN-FILL DEPOSITS

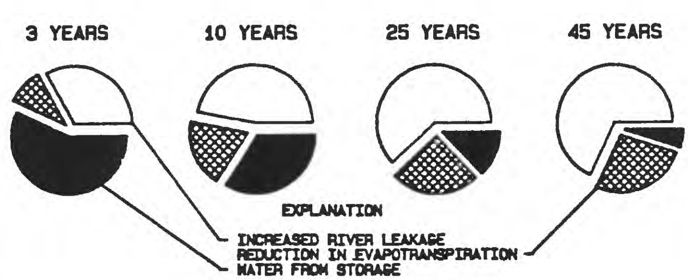
BEDROCK

CELL IN WHICH SIMULATED PUMPING IS INCREASED

CELL IN WHICH SIMULATED PUMPING CONTINUES AT EXISTING RATE

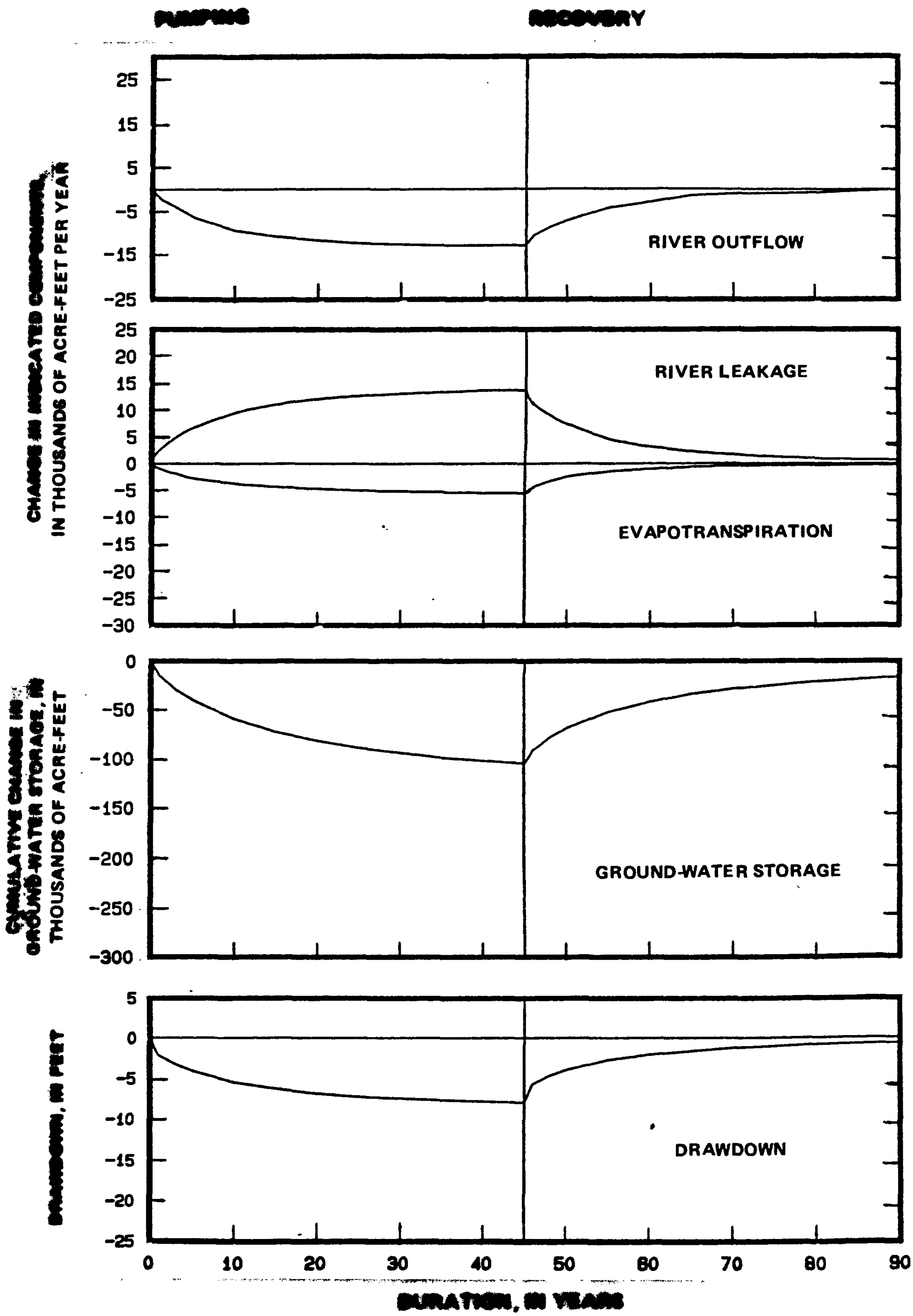
—10— LINE OF EQUAL DRAWDOWN -- Interval, in feet, is variable. Datum is water-level altitude at start of simulation

A. Areal distribution of drawdown after 45 years of increased pumping.



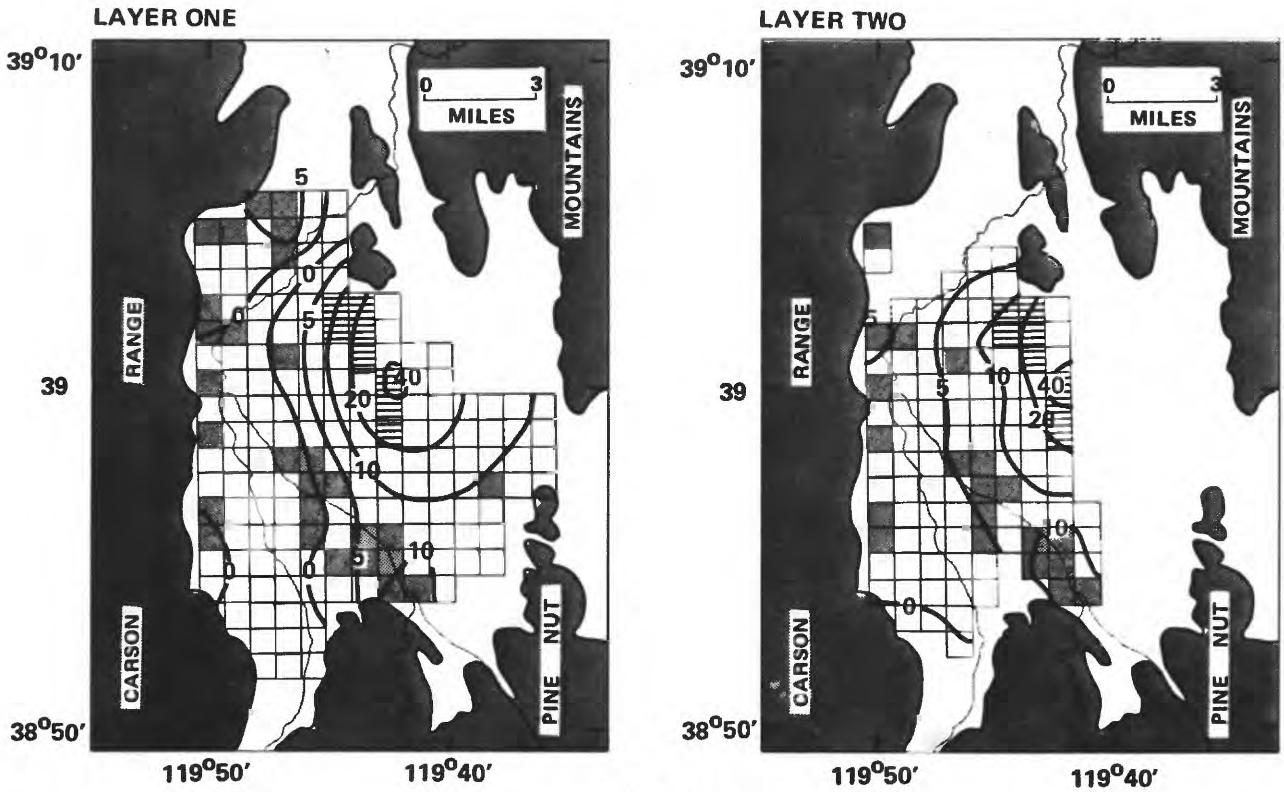
B. Sources of pumpage.

FIGURE 21.--Simulated response to 45-year period of increased pumping in the Buckeye area, and subsequent 45-year recovery.



C. Changes in river outflow, river leakage, evapotranspiration, ground-water storage, and drawdown. Drawdown is average for all cells in which increased pumping is simulated.

FIGURE 21.--Continued.



EXPLANATION

BASIN-FILL DEPOSITS

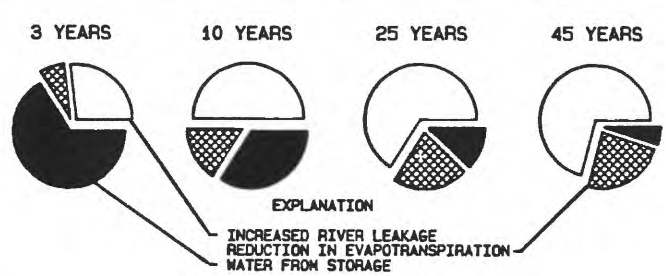
BEDROCK

CELL IN WHICH SIMULATED PUMPING IS INCREASED

CELL IN WHICH SIMULATED PUMPING CONTINUES AT EXISTING RATE

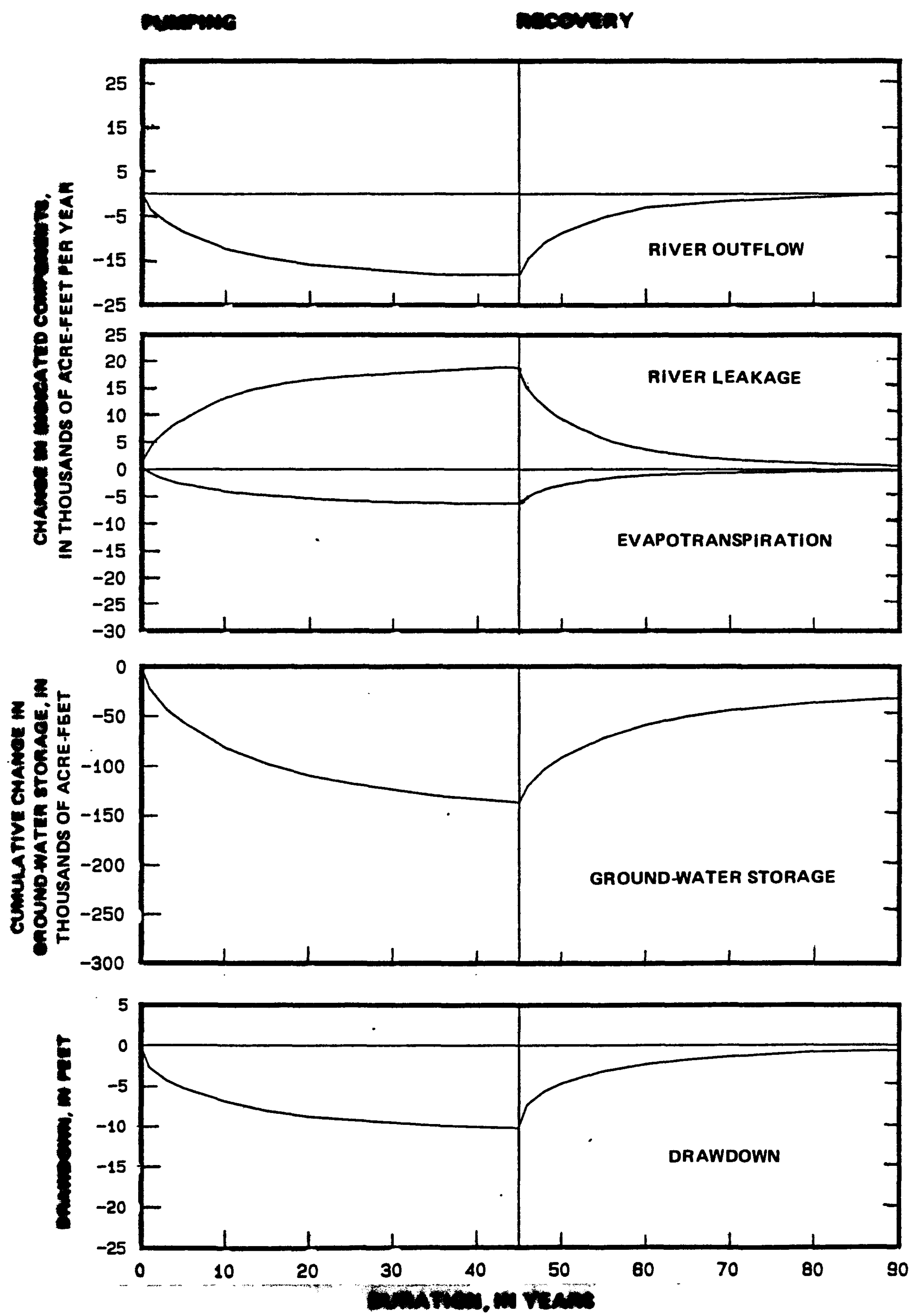
—5— LINE OF EQUAL DRAWDOWN -- Interval, in feet, is variable. Datum is water-level altitude at start of simulation

A. Areal distribution of drawdown after 45 years of increased pumping.



B. Sources of pumpage.

FIGURE 22.--Simulated response to 45-year period of increased pumping in the Buckeye and Johnson Lane areas, and subsequent 45-year recovery.



C. Changes in river outflow, river leakage, evapotranspiration, ground-water storage, and drawdown. Drawdown is average for all cells in which increased pumping is simulated.

FIGURE 22.--Continued.

In layer one, simulated drawdowns extend much farther to the east and south, and slightly farther to the west (figure 23A) than in the preceding simulations with continuing irrigation. To the west, the remaining irrigation outside the Buckeye and Johnson Lane areas maintain high ground-water levels. Layer-two drawdowns are about the same as for layer one on the east side of the valley, but drawdowns greater than 5 feet extend completely across the valley floor to the west. This is probably due to the capturing of a large part of the recharge on the eastern side of the valley floor by pumping, and the lack of stream leakage on the east side to replace that recharge. The extent of drawdown to the west indicates that streamflow supplies a significant portion of the recharge to the eastern side of the valley floor. In layer two, recharge from the western alluvial-fan deposits and ditch systems maintains water levels in the southwest corner of the valley.

Carson River outflow at the beginning of the third simulation is much higher than for steady-state simulations due to lack of irrigation and resulting leakage in the Buckeye area (figure 23C). As pumping continues, drawdown increases in areas farther south and west. River leakage increases, and Carson River outflow decreases only 5,000 acre-ft/yr more than for the simulation with no pumpage. Evapotranspiration rates decrease quickly at first, and, as the cone of depression expands, consumptive use in the Buckeye area is reduced. After the first 10 years of pumpage, evapotranspiration decreases more slowly; the final value is about 17,000 acre-ft/yr less than the steady-state rate. Storage greatly decreases, by about 300,000 acre-ft at the end of the pumping period, due to the lack of irrigation leakage coupled with the pumpage near Buckeye.

After simulated pumping stops, and with the irrigation system still removed from the area, Carson River outflow increases by almost 12,000 acre-ft/yr. Both river leakage and evapotranspiration decrease by about 12,000 acre-ft/yr, due to the lack of irrigation and a lower water table in the Buckeye area. Even after 45 years of recovery, lack of recharge from irrigation results in a permanent decrease in storage of about 200,000 acre-ft, which corresponds to a permanent decrease in water levels averaging 10 feet in the cells that are pumped in the Buckeye area. This land was not originally used for agricultural production. Irrigation ditches were dug and flood irrigation began in the early 1900's. The decrease in water levels represents a return to conditions existing before development for agricultural production and application of irrigation water.

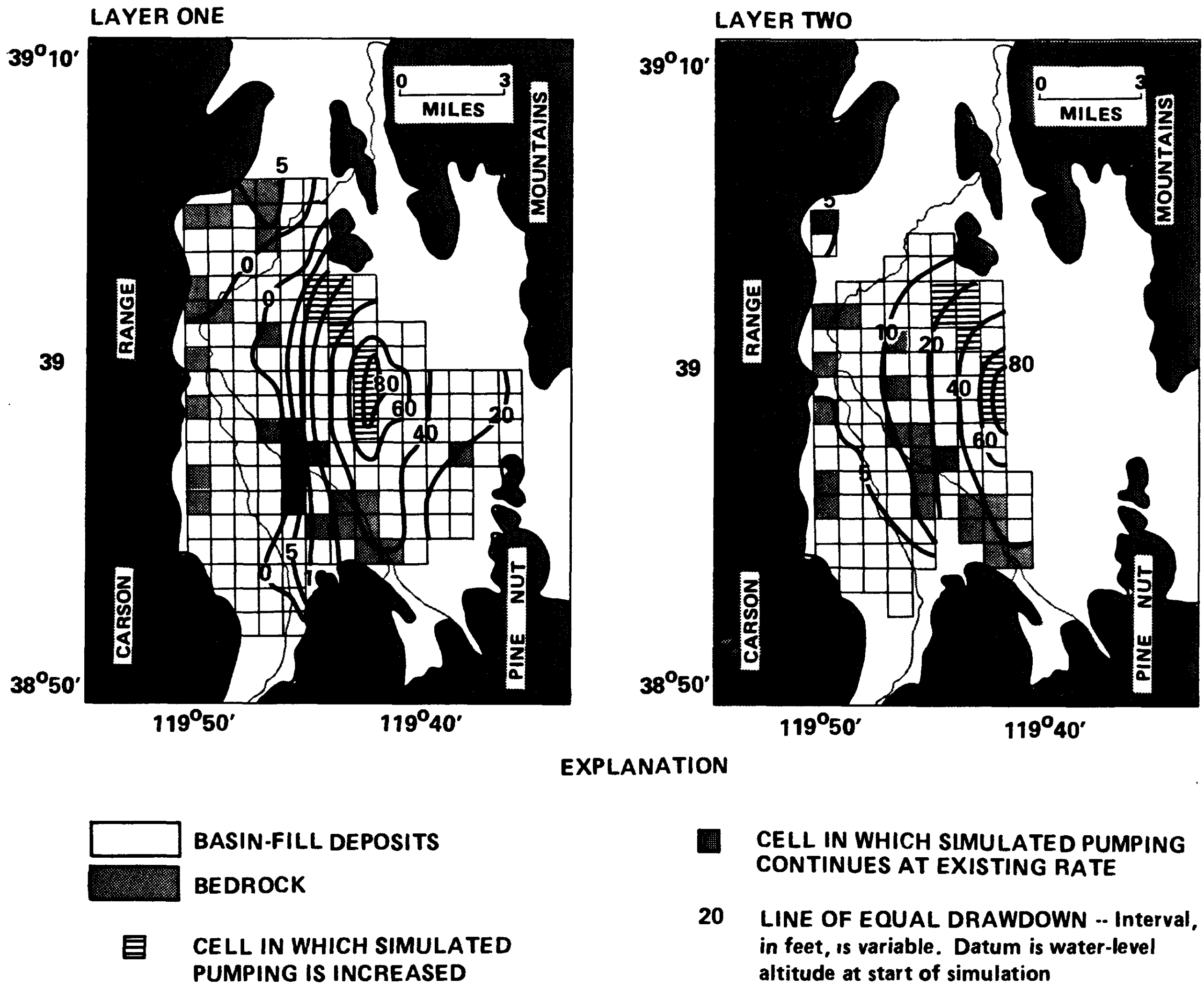
Due to increased drawdowns south of Gardnerville, where irrigation is still simulated, a greater percentage of pumped water comes from river leakage during the first 10 years of the pumping period than for the simulation with no land-use change (figure 23B). Evapotranspiration consumes slightly less water during the first 3 years as rates decrease in the Buckeye area. After 45 years of pumping, the ultimate sources for the pumped water are the same as before the change in land use.

Gardnerville Ranchos

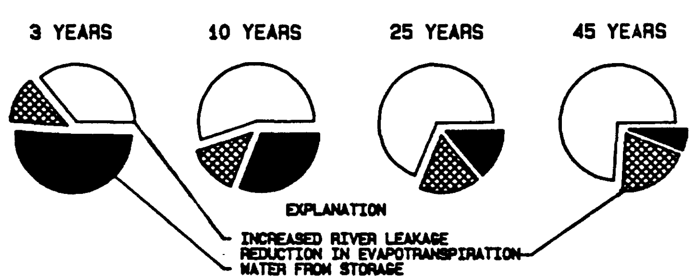
The fourth development scenario is in the Gardnerville Ranchos area near the south margin of the valley, where about 21,000 acre-ft/yr of pumpage is added to the average valley-wide base pumpage rate of 8,000 acre-ft/yr, in two rows of cells across the south end of the model area. Resulting drawdowns are greatest near the point where the East Fork of the Carson River enters the valley; drawdowns of as much as 5 feet extend north as far as the Buckeye area (figure 24A). Simulated drawdowns toward the north are probably in response to capture of recharge in that area by the pumping applied in the Ranchos area. Drawdowns on the western side of the valley are less than 5 feet in the pumped nodes, and they increase to more than 5 feet in cells adjacent to the southwest model boundary. As seen in figure 15, these cells do not receive irrigation recharge, and the nearby pumpage exceeds the natural subsurface recharge from the Carson Range, resulting in the drawdown. In layer two, drawdown is more extensive over the south end of the valley; as with the preceding scenarios, it is greatest on the east side--up to 40 feet--and decreases to about 10 feet on the west side of the valley. A drawdown of at least 5 feet extends to just north of Minden across the whole model area.

The simulated additional pumping in the Gardnerville Ranchos area results in Carson River outflow decreasing by about the magnitude of the increased pumpage--22,000 acre-ft/yr (figure 24C). River leakage is increased and evapotranspiration loss is about the same as that for the combined Buckeye and Johnson Lane pumpage, storage depletion after 45 years of pumping totals about 94,000 acre-ft, with a mean drawdown in the pumped cells of about 12 feet. After cessation of pumping, recovery is slightly faster than for the scenarios with pumping on the east side of the valley, probably as a result of higher streambed conductivities on the west side. Carson River outflow, river leakage, and evapotranspiration all recover less than 35 years after the cessation of pumping, and ground-water levels and storage do not quite recover after 45 years.

At the beginning of the pumping period, river leakage supplies more water for pumpage in the Ranchos area than for simulations of increased pumpage on the east side of the valley (figure 24B). Less water originates from storage, and evapotranspiration rates remain about the same. By the end of the 45-year pumping period, river leakage has increased and supplies about 75 percent of the pumped water--only a slight increase over leakage induced by scenarios with pumping on the east side of the valley. Reduction in evapotranspiration and storage contributes slightly less to pumpage than for pumpage on the east side of the valley.

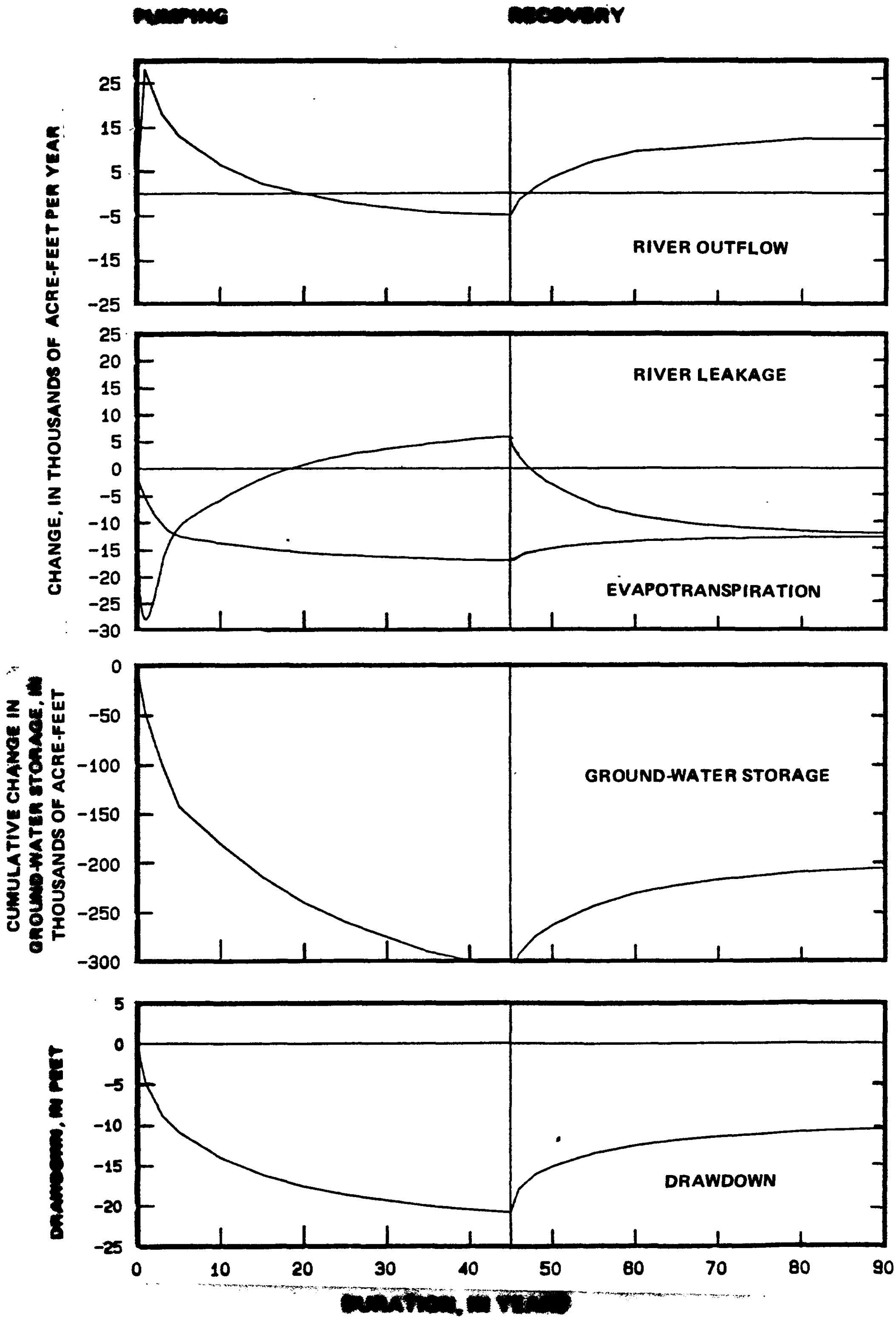


A. Areal distribution of drawdown after 45 years of increased pumping.



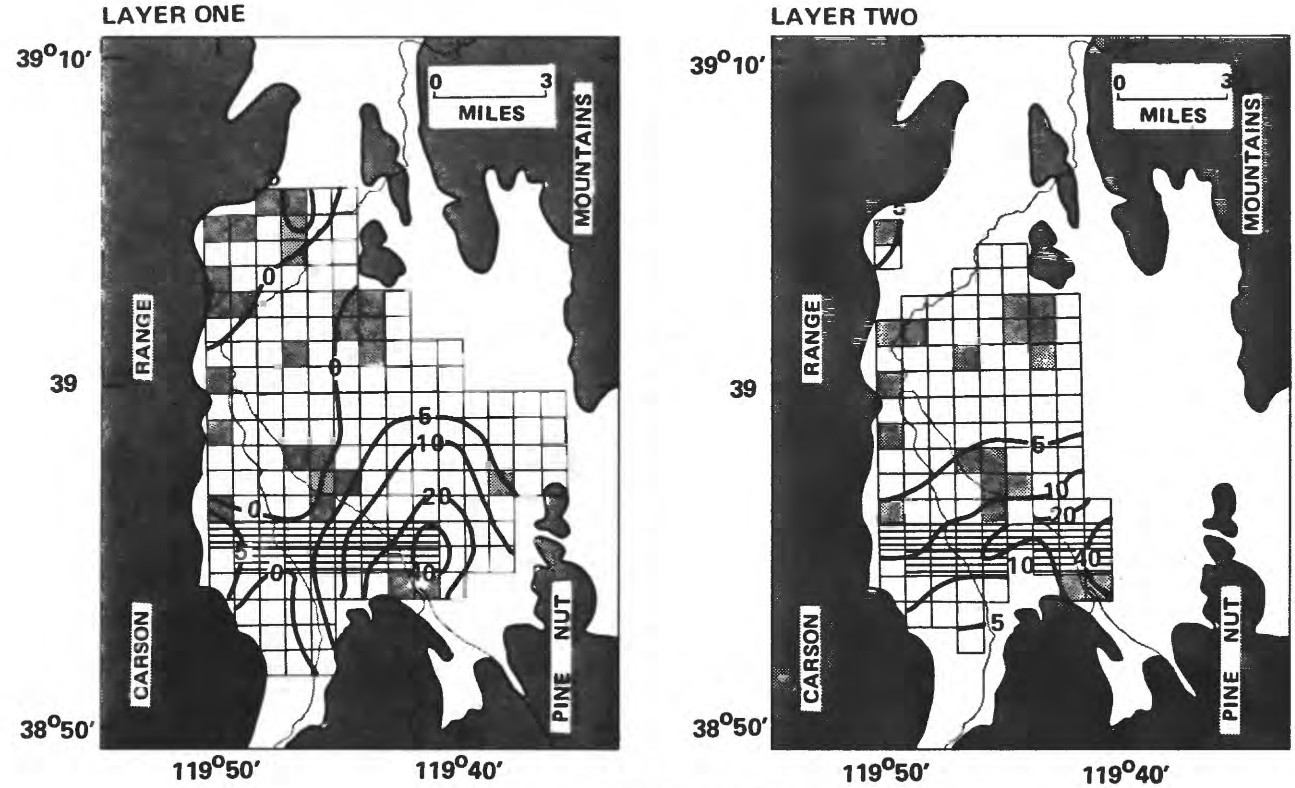
B. Sources of pumpage.

FIGURE 23.--Simulated response to 45-year period of increased pumping in the Buckeye and Johnson Lane areas, with no irrigation, and subsequent 45-year recovery.



C. Changes in river outflow, river leakage, evapotranspiration, ground-water storage, and drawdown. Drawdown is average for all cells in which increased pumping is simulated.

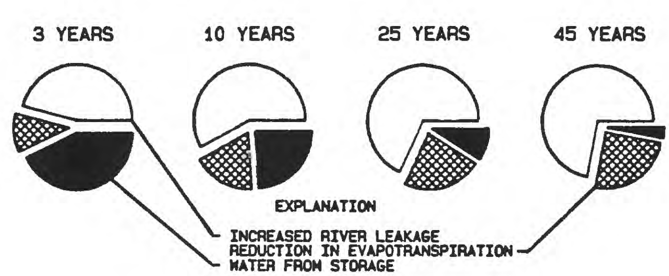
FIGURE 23.--Continued.



EXPLANATION

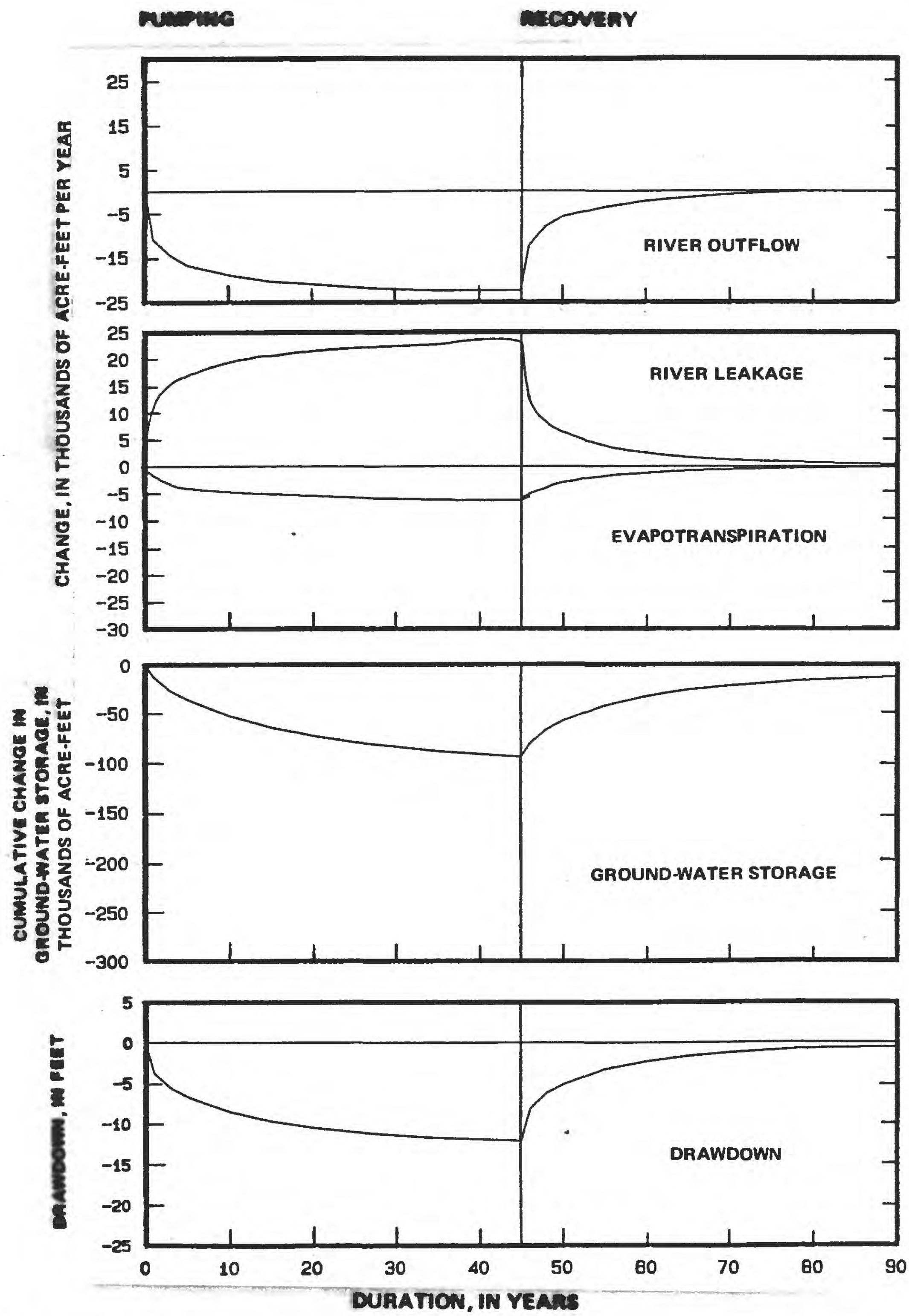
- BASIN-FILL DEPOSITS
- BEDROCK
- CELL IN WHICH SIMULATED PUMPING IS INCREASED
- CELL IN WHICH SIMULATED PUMPING CONTINUES AT EXISTING RATE
- —10— LINE OF EQUAL DRAWDOWN -- Interval, in feet, is variable. Datum is water-level altitude at start of simulation

A. Areal distribution of drawdown after 45 years of increased pumping.



B. Sources of pumpage.

FIGURE 24.--Simulated response to 45-year period of increased pumping in the Gardnerville Ranchos area, and subsequent 45-year recovery.



C. Changes in river outflow, river leakage, evapotranspiration, ground-water storage, and drawdown. Drawdown is average for all cells in which increased pumping is simulated.

FIGURE 24.--Continued.

Western Alluvial Fans

The fifth scenario involves pumpage along the west side of the valley, where development is now occurring in small scattered subdivisions. A hypothetical pumpage of 13,000 acre-ft/yr is applied in addition to the valley-wide average base pumpage of 8,000 acre-ft/yr.

Large drawdowns in layer one are confined to those cells that are not receiving irrigation recharge (figure 25A). Drawdowns in cells where both pumping and irrigation recharge occur are only about 1 foot. A much greater effect due to pumping is seen in layer two, where drawdowns of at least 5 feet extend to the Gardnerville area and U.S. Highway 395.

The effect of pumping on storage and average drawdown was less than in the previous simulations, because these values change only in relatively few cells (figure 25C). Carson River outflow is decreased by about 18,000 acre-ft/yr, which induces about the same amount of river leakage as in previous simulations. In contrast, decreases in evapotranspiration are small--only 3,000 acre-ft/yr. The small change in evapotranspiration is probably due to the small drawdowns in layer one, which are not sufficient to significantly decrease evapotranspiration losses.

Following cessation of pumping, recovery of Carson River outflow, river leakage and evapotranspiration is quick compared to other scenarios, and drawdowns recover but storage does not quite recover after 45 years.

River leakage supplies much of the pumped water early in the simulation (figure 25B). By the end of the 45-year pumping period, about 85 percent of the pumped water originates from river leakage; the remainder is supplied mainly by a depletion of ground-water storage and a minor reduction in evapotranspiration.

Pumpage at Maximum Buildout

The sixth and final development scenario involved the application of an amount of municipal and domestic pumpage estimated to accompany the maximum buildout allowed by the master land-use plan for Douglas County, which totals 13,600 acre-ft/yr. (Pumped quantities in the previous scenarios, some of which exceed this quantity, were hypothetical, and assumed revisions of the master plan.) In addition to this pumpage, a total agricultural pumpage of 6,400 acre-ft/yr is also applied to cells having that type of pumpage during the calibration period, which represents the estimated agricultural pumpage for water year 1981, a dry year; thus, the simulation represents a "worst case" scenario.

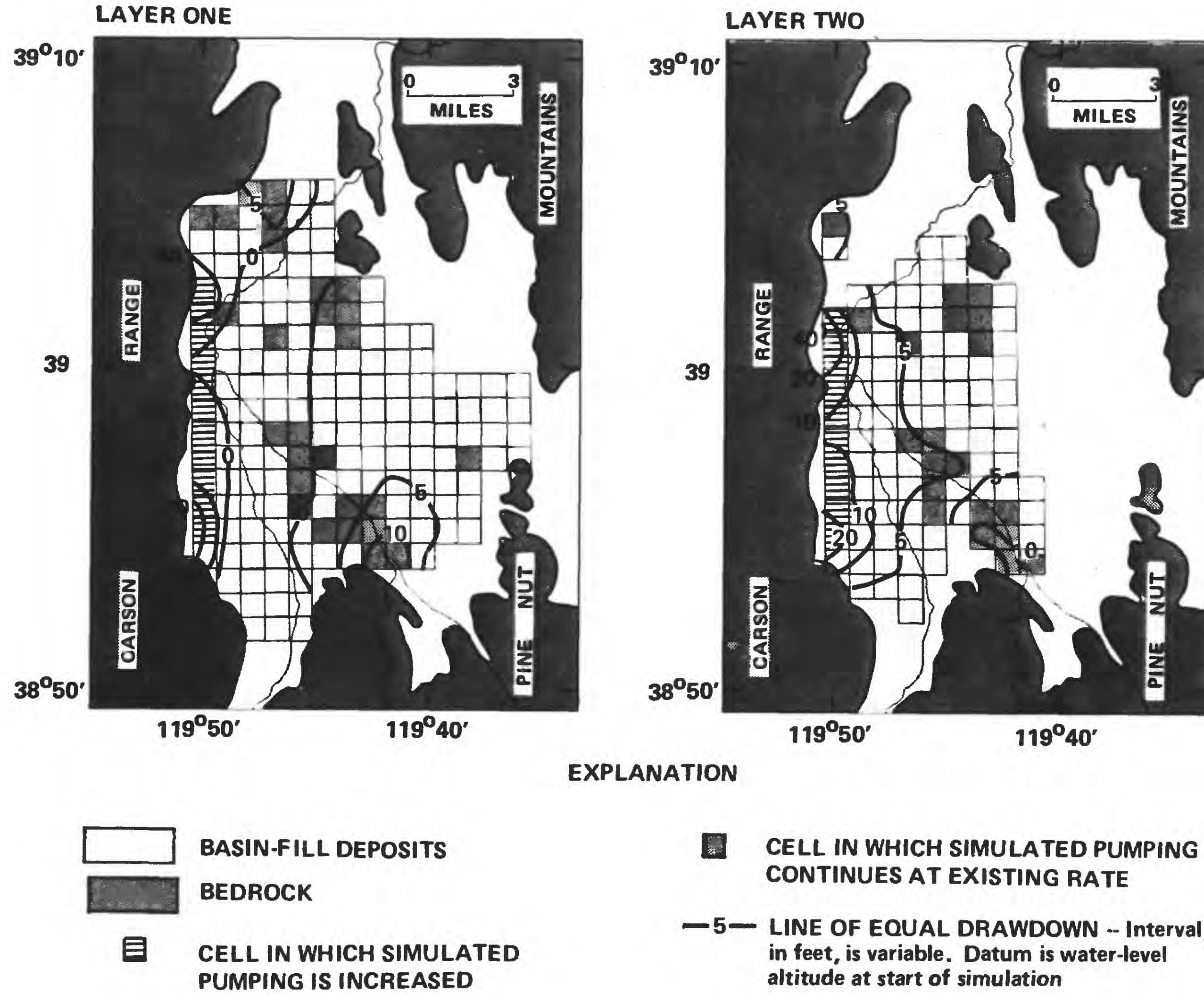
Simulated drawdowns in layer one are greatest at the model boundary, and between 5 and 10 feet throughout almost the entire east side of the valley (figure 26A). Simulated water levels on the valley floor are relatively unaffected except toward the north end, where drawdowns are between 0 and 5 feet. A small area with a 5-foot drawdown exists on the west side of the valley floor near Sheridan. The northeast corner of the valley experiences drawdowns from 10 to 40 feet as a result of agricultural pumpage in the Jacks Valley area and drawdowns up to 20 feet as a result of domestic and municipal pumpage in the Indian Hills area.

Drawdowns in layer two also are greatest--up to 20 feet--in the southeast corner of the valley and are greater than 5 feet on the entire east side of the valley from Hot Springs Mountain south to Minden. Drawdown on the valley floor in layer two is less than 5 feet. Agricultural pumpage in the Jacks Valley area causes drawdowns of 5 to 20 feet in layer two.

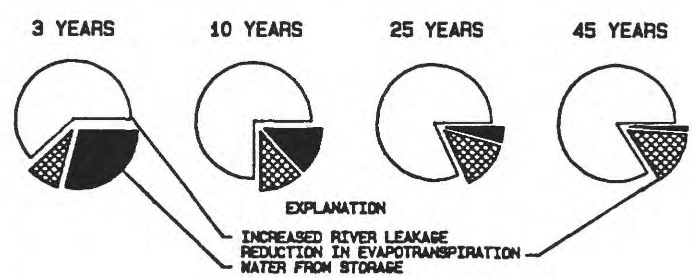
Long-term Carson River outflow is affected less than for previous scenarios, decreasing by only about 14,000 acre-ft/yr (figure 26C). This is probably the result of the pumping being spread rather evenly throughout the valley, with drawdown at pumping nodes averaging only about 7 feet. Stream leakage is increased by about 14,000 acre-ft/yr and evapotranspiration is decreased by about 5,000 acre-ft/yr. Ground-water storage is decreased by about 80,000 acre-ft after the 45-year pumping period.

Carson River outflow, river leakage, and evapotranspiration recover in 45 years, but drawdown and storage do not.

Pumped water at the beginning of the simulation is mainly from storage, amounting to 52 percent, with 12 percent from evapotranspiration and 36 percent from stream leakage (figure 26B). By the end of the simulation, 70 percent of the pumped water originates from stream leakage, 25 percent from evapotranspiration, and only 5 percent from ground-water storage depletion.

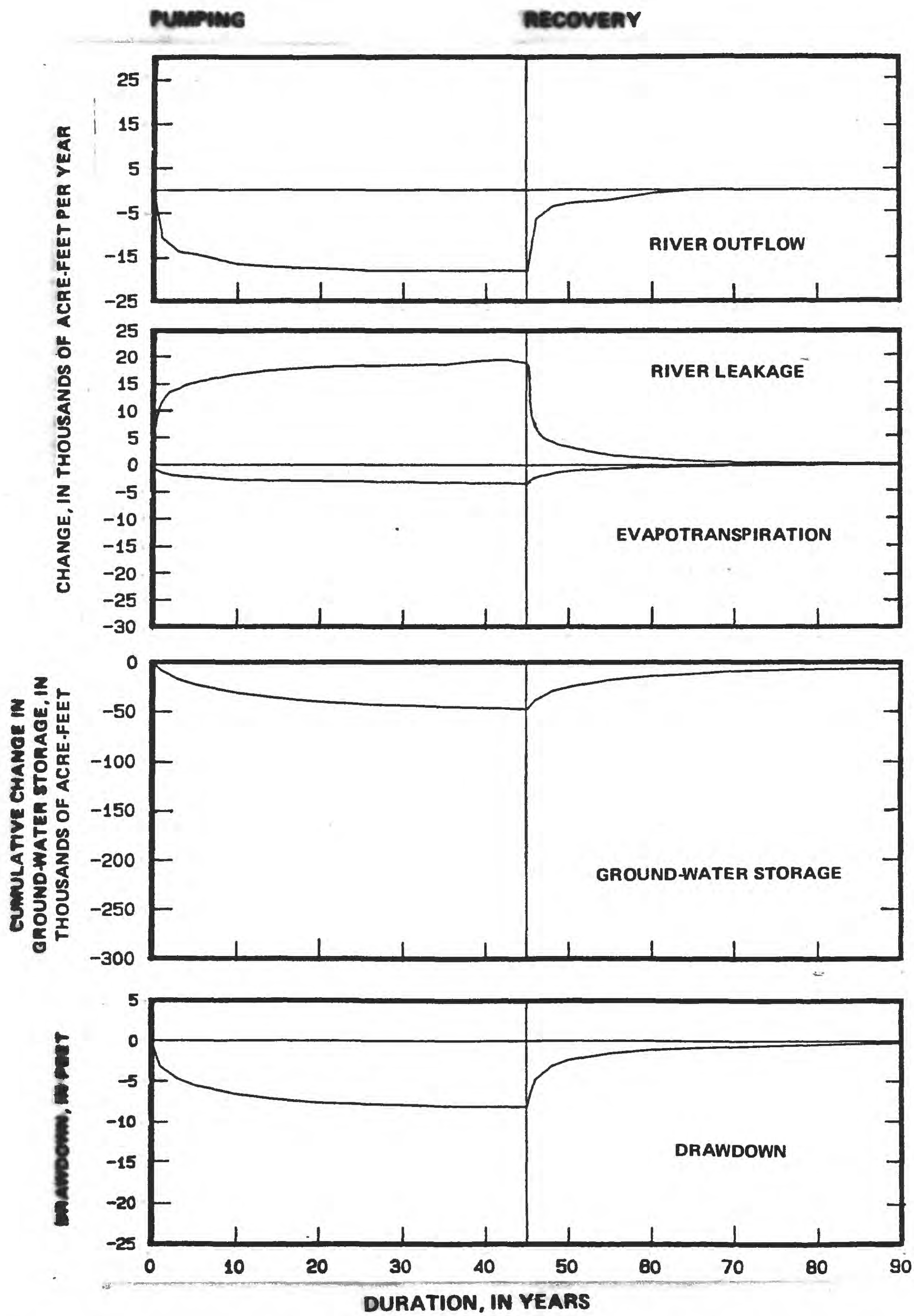


A. Areal distribution of drawdown after 45 years of increased pumping.



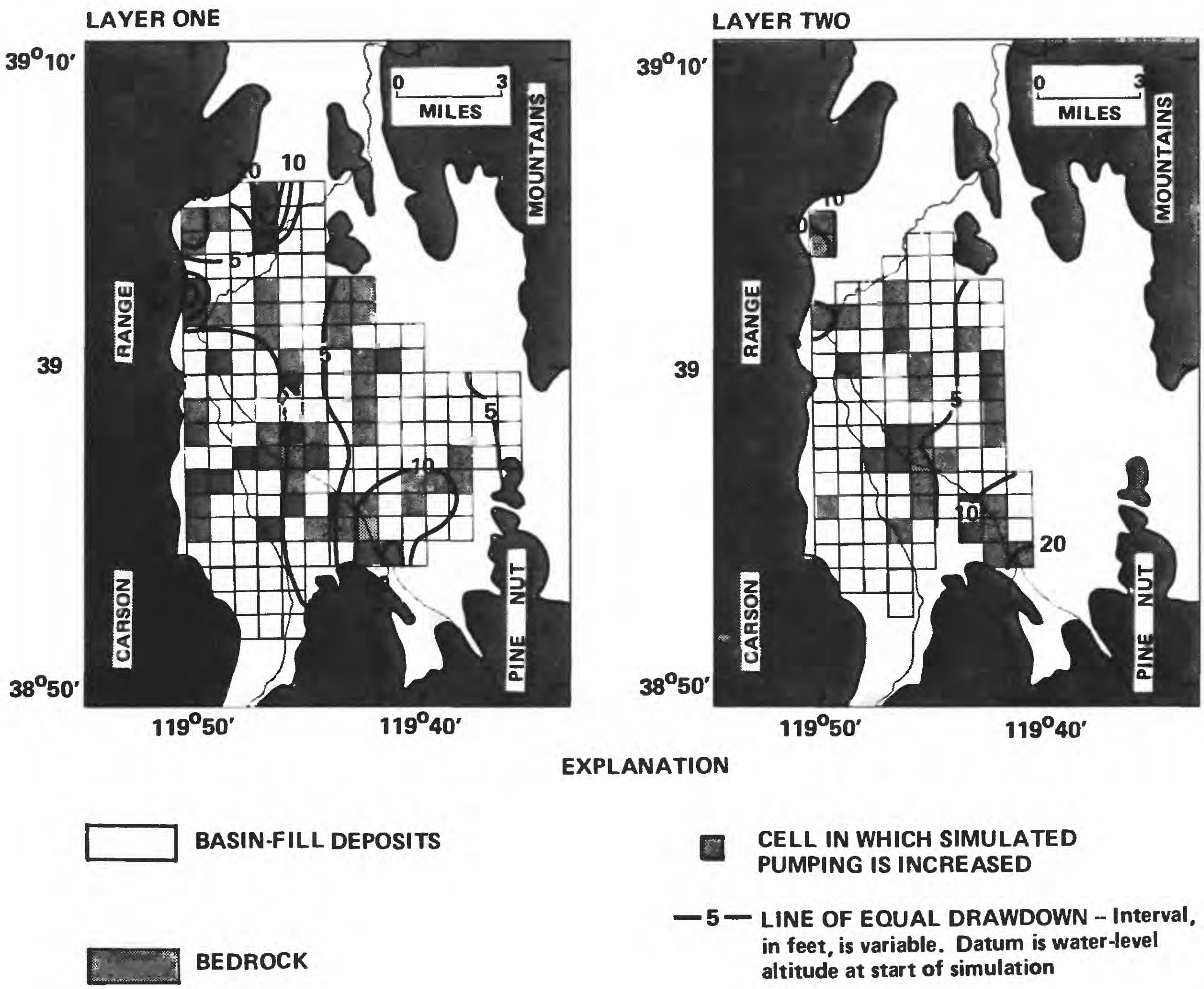
B. Sources of pumpage.

FIGURE 25.--Simulated response to 45-year period of increased pumping on the western alluvial fans, and subsequent 45-year recovery.

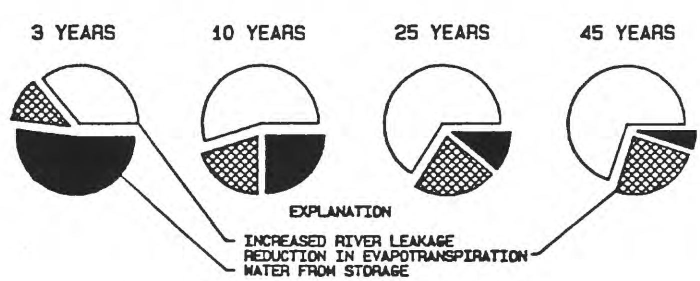


C. Changes in river outflow, river leakage, evapotranspiration, ground-water storage, and drawdown. Drawdown is average for all cells in which increased pumping is simulated.

FIGURE 25.--Continued.

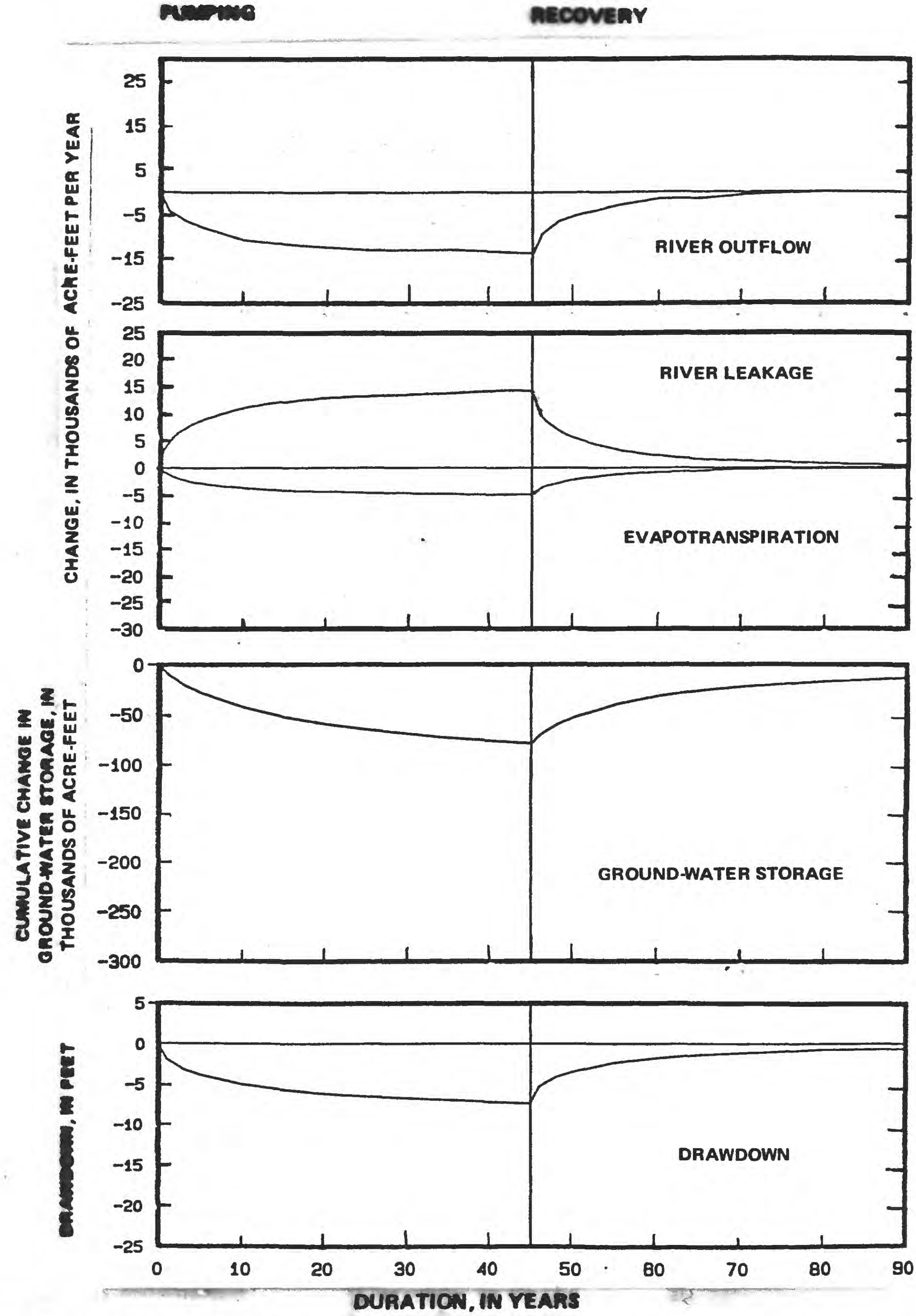


A. Areal distribution of drawdown after 45 years of increased pumping.



B. Sources of pumpage.

FIGURE 26.--Simulated response to 45-year period of increased pumping at maximum valley-wide buildout, and subsequent 45-year recovery.



C. Changes in river outflow, river leakage, evapotranspiration, ground-water storage, and drawdown. Drawdown is average for all cells in which increased pumping is simulated.

FIGURE 26.--Continued.

SUMMARY AND CONCLUSIONS

Drillers' logs and depth-to-bedrock data provided information on the geohydrologic setting of Carson Valley and permitted estimates of hydraulic conductivity and thickness of aquifer materials. The drillers' logs, along with streamflow data and monthly measurements of ground-water levels, provided a basis for evaluating the major hydrologic processes in the valley.

The basin-fill reservoir was divided into two geohydrologic units, one consisting of unconsolidated alluvial-fan sediments and fluvial sediments of the Carson River, which are of Quaternary age, and another consisting of partly consolidated sediments of Tertiary age. The Tertiary unit crops out mainly on the east side of the valley, but is probably present at appreciable depth beneath the Quaternary unit on the valley floor.

Both confined and unconfined aquifers exist in the Quaternary unconsolidated unit. Unconfined water levels are within 5 feet of land surface on the valley floor, but increase to over 100 feet in depth near the perimeter of the valley. Confined water levels as much as 20 feet above land surface are found (1) in wells more than 200 to 300 feet deep on the valley floor, and (2) in wells less than 100 feet deep near the alluvial fans on the west side of the valley. Water levels and drillers' logs from wells in the Tertiary unit indicate that the water moves through thin layers of coarser sediment that are separated by thick confining layers of silt and clay.

Precipitation recharges the basin-fill reservoir by (1) subsurface flow through weathered or fractured zones in the surrounding bedrock and into alluvial-fan deposits on the west side of the valley and into Tertiary sediments on the east side of the valley, (2) infiltration of runoff into the basin-fill reservoir, and (3) percolation of precipitation on the basin-fill reservoir. Water-level fluctuations indicate that the western alluvial-fan deposits conduct recharge to both the unconfined and confined aquifers on that side of the valley. The confined aquifer also receives recharge from percolation of surface water in the upstream parts of the valley floor and from the Tertiary unit on the east side of the valley. Water-level fluctuations also suggest that the unconfined aquifer receives upward recharge from the confined aquifer and downward recharge from surface-water irrigation.

Aquifer characteristics and components of inflow to and outflow from the basin-fill reservoir were estimated, and ground-water pumpage and rates of land application of sewage effluent were compiled, for calibration of a numerical model of ground-water and surface-water flow.

Estimation of flow components in the basin-fill reservoir allowed calculation of a preliminary water budget. The flow of the Carson River dominates the hydrologic regimen of the valley; long-term inflow is about 360,000 acre-ft/yr and outflow is about 291,000 acre-ft/yr. Another dominant component of the water budget is outflow due to potential evapotranspiration and evaporation from surface-water bodies, totaling about 200,000 acre-ft/yr. Mean annual precipitation falling on the basin-fill reservoir totals about 70,000 acre-ft/yr; about 38,000 acre-ft/yr enters the reservoir by subsurface inflow; and runoff from mountain-block streams is about 24,000 acre-ft/yr.

Steady-state calibration of the model was achieved by matching water levels observed in March 1982, which approximate average conditions, with simulated water levels, and by matching observed and simulated surface-water outflow from the valley. Steady-state simulations calculated a net loss from surface-water flows to the basin-fill reservoir of about 44,000 acre-ft/yr, and a net loss from the basin-fill reservoir to evapotranspiration and evaporation from surface-water bodies of about 170,000 acre-ft/yr. Substitution of these values in the preliminary water budget provides a balance between estimates of inflow to and outflow from the basin-fill reservoir. Thus, the model matches the observed steady-state conditions implied by the lack of measurable change in water levels between 1956 and 1981. However, storage depletion caused by existing pumpage presumably is offset by streamflow leakage (percolation), and any long-term decrease in Carson River outflow induced by the relatively small pumping rates as of 1983 would be masked by annual variations in precipitation and river outflow.

Transient calibration was achieved by matching observed variations in ground-water levels, ground-water storage, and surface-water flows during a 3-year period (water years 1981-83, October 1980-September 1983) that included dry conditions in 1981 to a record wet year in 1983. The calibrated model provided a good fit to observed data; surface-water outflow was simulated to within an average of 20 percent of flows measured during the calibration period. In addition, calibration was further tested by comparing simulated to observed surface-water outflows for 2 additional water years (1975 and 1976) outside the calibration period; for these years, trends in simulated outflows agreed with the observed flows within an average error of 30 percent.

Flow budgets show that upward leakage from model layer two (deep) to layer one (shallow) is almost constant, totaling about 19,000 acre-ft/yr and is providing a steady source of recharge to layer one. Increased stream leakage is induced during dry years, when pumping and evapotranspiration cause water-level declines and correlative decreases in ground-water storage.

Sensitivity runs showed that hydraulic conductivity and recharge to the valley from the surrounding mountain blocks were the most critical model elements, and that specific yield of layer one and storage coefficients for layer two were the least sensitive, with respect to simulated head. Recharge and evapotranspiration were not critical with respect to Carson River outflows.

Simulations of hypothetical pumping increases in several areas of the valley (table 13) indicate that Carson River outflow is directly affected by the increased pumping, owing to the extensive flood-irrigation system that provides recharge to replenish ground water in the shallow aquifer system. Where irrigation is active, drawdown due to pumping is only a few feet; as the gradient between the irrigation system and the water table increases, the volume of water percolating to the water table also increases, which in turn decreases Carson River outflow from the valley. The response of Carson River outflow to increased ground-water pumping may be a gradual decrease in mean annual flow over many years' time. However, annual variation in precipitation and river outflow may mask changes in Carson River outflow due to ground-water pumpage.

In the simulations of hypothetical development, changes in drawdown, storage, and evapotranspiration on the valley floor due to pumping are minimal because Carson River flow replenishes most of the pumped water. On the margins of the valley, however, pumping causes a greater change in these values because river flow is not available, and subsurface recharge is captured. This causes an extension of drawdowns toward the valley floor and, eventually, also induces leakage from the surface-water system.

Simulations indicated that changes in land use from agricultural to urban on the east side of Carson Valley can affect Carson River outflows, ground-water levels, and storage to a greater degree than an increase in pumping can. In this area, development of the flood-irrigation system in years past caused water levels to rise above those existing before the land was put into production. Thus, removal of irrigation would cause a return to pre-development water levels and a decrease of leakage from the surface-water system, along with an increase in Carson River outflow. In all simulations of hypothetical development, pumped water is assumed to be totally consumed. The effects of potential changes in secondary recharge of pumped water and imported sewage effluent were not considered in the simulations, owing to the large uncertainty of where and how this water will be distributed and used in the future.

TABLE 13.--*Summary of hydrologic response to simulated ground-water pumping in selected areas*

Area with simulated additional pumping	Buckeye	Buckeye plus Johnson Lane	Same, without irrigation	Gardnerville Ranchos	Western alluvial fans	Maximum buildout
Total amount of pumping (acre-ft/yr)[1]	20,000	25,000	25,000	29,000	21,000	[a]20,300
Change after 45 years of pumping:						
River outflow (acre-ft/yr)	-13,000	-18,000	-5,000	-22,000	-18,000	-14,000
Evapotranspiration (acre-ft/yr)	-6,000	-6,000	-17,000	-6,000	-3,000	-5,000
Ground-water storage (acre-ft)	-100,000	-140,000	-300,000	-94,000	48,000	-80,000
Net change after 45 years of pumping and 45 years of recovery:						
River outflow (acre-ft/yr)	0	0	+12,000	0	0	0
Evapotranspiration (acre-ft/yr)	0	0	-12,000	0	0	0
Ground-water storage (acre-ft)	-17,000	-31,000	-200,000	-12,000	-7,000	-13,000

[1] Includes valley-wide "background" pumpage of 8,000 acre-ft/yr (the average amount estimated in water years 1981-83), except as noted otherwise.

[a] Includes 6,400 acre-ft/yr of agricultural pumpage (the amount estimated for water year 1981).

These results represent the application of data available as of 1983 for use in analyzing large-scale hydrologic relations in Carson Valley. Evapotranspiration of water by crops as of 1983 was by far the largest component of ground-water outflow in Carson Valley, with pumpage representing only a small percentage of total water use. The relatively unstressed nature of the ground-water reservoir at that time may require additional refinements and adjustments to the model when pumpage increases or land use changes. The simulations of Carson River outflows and water-level changes should be considered only as indications of long-term trends.

TOPICS FOR POSSIBLE FURTHER STUDY

Continued water-level measurements and collection of pumpage data, on at least an annual basis, would help to determine whether long-term changes are taking place in Carson Valley. Of special interest are (1) areas along the western alluvial fans, where pumpage could more readily exceed natural recharge, (2) the Jacks Valley area, where a lack of observation wells and complicated hydrogeology make predictions rather difficult, (3) the area where the East Fork of the Carson River enters the valley, for which simulations indicate that the response to pumpage is quickest, and (4) any other area where extensive development takes place.

The transition between the Tertiary sediments that are exposed on the east side of the valley and the sediments beneath the valley floor is a poorly understood geologic relation. Additional well data and aquifer tests along the east side of the valley floor would provide much more information on (1) the subsurface geology of the area and (2) the means by which ground water moves from the Tertiary sediments into the Quaternary ground-water system beneath the valley floor.

Because recharge to the alluvial-fan deposits on the west side of the valley is critical to predicted drawdowns there, a refinement of the estimates of subsurface and surface-water inflow, and a more accurate determination of the loss of mountain-block streamflow by infiltration, would be useful.

Estimates of secondary recharge of pumped water for the various types of land and water use (irrigation, domestic pumpage with lawn irrigation and septic tanks, and municipal pumpage with lawn irrigation and municipal sewage treatment) also would be useful.

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